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THE RECTANGULAR SYSTEM OF UNITED STATES PUBLIC LAND SURVEYING.

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IT is a well known fact that among civil engineers of this country the theory and practice of public land surveying is not thoroughly understood, and the admirable features of the rectangular method have not received the recognition they deserve.

In the bulky volumes of the great trigonometrical survey of India, which work was accomplished many years ago at an expenditure of years of labor and thousands of pounds sterling, we see an accurate record of a magnificent scientific achievement, the result of which has been that that far-off region is faithfully mapped and monumented for future generations, and the configuration of such a vast territory so clearly determined as to have a bearing upon the ascertainment of the exact shape of the globe itself. Such a result is valuable for scientific and strategical purposes, but has not the economic uses of our public land survey system.

In the public domain of our country a plan, which became the law, was devised by a Committee of the Continental Congress, headed by Thomas Jefferson, whereby the unoccupied and unappropriated land could be so divided up as to enable settlers to obtain equitable portions of the land, and so fix and determine the boundaries of the smallest tract that no confusion or conflict would arise. The wisdom

of this plan is made manifest every day. Over the great plains and rich valleys, as well as the rugged sides of the Rockies, there are symmetrical squares of land definitely and accurately described, not by metes and bounds, but by location, which contain forty, eighty, and one hundred and sixty acre tracts, the homes of the millions now domiciled, and the countless numbers yet to come, upon the vast domain which fifty years ago was an unbroken wilderness inhabited by red men and buffaloes. This plan has been modified and improved by various acts of Congress, but the inceptional design has not been changed.

A few years ago our Canadian brethren found themselves confronted by the problem of dividing up their own extensive territory in preparation for the settlement by the constantly increasing squatters in the British Possessions; and it was a high compliment to the rectangular system of United States public land surveys when they adopted practically our methods. To be sure, there were one or two so-called improvements made by them, but they are minor changes, and their utility has been questioned by experts.

The *United States Coast and Geodetic Survey* has charge of the survey of the Atlantic, Gulf, and Pacific coasts of this country, including the coasts of Alaska, the survey of rivers to the head of tide-water or ship navigation; deep-sea soundings, temperature and current observations along the said coasts and throughout the Gulf Stream and Japan Stream flowing off from them; magnetic observations and gravity researches, determinations of heights by geodetic leveling, and of geographical positions by lines of transcontinental triangulation which, with other connecting triangulations and observations for latitude, longitude, and azimuth, furnish points of reference for State surveys and connect the work on the Atlantic coast with that on the Pacific.

The *United States Geological Survey* has charge of the classification of the public lands and examination of the geological structure, mineral resources, and products of the national domain, and of survey of boundaries of forest reserves.

The *Hydrographic Survey* under the Department of the Navy is engaged upon the preparation of maps of foreign coasts and harbors for the use of our navigators.

The *Nautical Almanac* office, under the same department, prepares valuable tables and formulæ showing right ascensions, declinations, occultations of the heavenly bodies, for use of navigators and for gen-

eral scientific use in surveying operations demanding astronomical observations.

Upon the Commissioner of the General Land Office devolves the important duty of carrying forward the public land surveys, and under him the direction of the work is entrusted to the Division of Public Surveys of that office.

The surveying is done principally under contract with experienced engineers who are called deputy surveyors. In each of the surveying districts of the West, viz., Arizona, California, Nevada, Oregon, Washington, Idaho, Utah, New Mexico, Colorado, Montana, Wyoming, North Dakota, South Dakota, Minnesota and Alaska, a Surveyor General is appointed by the President, with authority to make contracts for surveys, subject to the approval of the Commissioner of General Land Office. He has in his office clerks and draftsmen who prepare the finished returns for transmittal to Washington. The sum of $325,000 is annually appropriated by Congress to pay for the surveys, which is exclusive of the amounts set apart by Congress for the salaries and expenses of the Surveyors General and their corps of clerks.

The Rectangular System.

"Existing law requires that in general the public lands of the United States 'shall be divided by north and south lines run according to the true meridian, and by others crossing them at right angles so as to form townships 6 miles square,' and that the corners of the townships thus surveyed 'must be marked with progressive numbers from the beginning.'

"Also, that the townships shall be subdivided into thirty-six sections, each of which shall contain 640 acres, as nearly as may be, by a system of two sets of parallel lines, one governed by true meridians and the other by parallels of latitude, the latter intersecting the former at right angles, at intervals of a mile.

"In the execution of the public surveys under existing law, it is apparent that the requirements that the lines of survey shall conform to true meridians, and that the townships shall be 6 miles square, taken together, involve a mathematical impossibility due to the convergency of the meridians.

"Therefore, to conform the meridional township lines to the true meridians, produces townships of a trapezoidal form which do not contain the precise area of 23,040 acres required by law, and which dis-

crepancy increases with the increase in the convergency of the meridians, as the surveys attain the higher latitudes.

"In view of these facts, and under the provisions of Section 2 of the Act of May 18, 1796, that sections of a mile square shall contain 640 acres *as nearly as may be*, the public lands of the United States are surveyed under the methods of the system of rectangular surveying, which harmonizes the incompatibilities of the requirements of law and practice, as follows:

"*First.* The establishment of a principal meridian conforming to the true meridian, and at right angles to it, a base line conforming to a parallel of latitude.

"*Second.* The establishment of standard parallels conforming to parallels of latitude, initiated from the principal meridian at intervals of 24 miles and extended east and west of the same.

"*Third.* The establishment of guide meridians conforming to true meridians, initiated upon the base line and successive standard parallels at intervals of 24 miles, resulting in tracts of land 24 miles square, *as nearly as may be*, which are subsequently divided into tracts of land 6 miles square by two sets of lines, one conforming to true meridians, crossed by others conforming to parallels of latitude at intervals of 6 miles, containing 23,040 acres, *as nearly as may be*, and designated *townships*.

"Any series of contiguous townships situated north and south of each other, constitute a *range*, while such a series situated in an east and west direction constitute a *tier*.

"The tiers of townships are numbered to the north or south, commencing with No. 1 at the base line, and the ranges of the townships to the east or west, beginning with No. 1 at the principal meridian of the system.

"The thirty-six sections into which a township is subdivided are numbered, commencing with number *one* at the *northeast* angle of the township, and proceeding west to number six, and thence proceeding east to number twelve, and so on, alternately, to number thirty-six in the southeast angle. In all cases of surveys of fractional townships, the sections bear the same numbers they would have if the township were full.

"Standard parallels are established at intervals of every 24 miles north and south of the base line, and guide meridians at intervals of every 24 miles east and west of the principal meridians, thus confin-

ing the errors resulting from convergence of meridians and inaccuracies in measurement within comparatively small areas." — *Manual of Surveying Instructions, 1894.*

How Public Land Surveys are Initiated.

In order to obtain a survey of public land, application is made to the Surveyor General of the district where the lands are situated, by settlers, at least three for every tract 6 miles square, whose petition must set forth that they are *bona fide* settlers, and that they have made valuable improvements. The Surveyor General forwards the petition to the General Land Office at Washington and asks for authority to contract for a survey of the land. If the application be properly supported, the Surveyor General is instructed to take the necessary steps to have the survey made.

If there appear to be involved the payment of the minimum or intermediate rates, which are hereinafter explained, the Surveyor General can at once enter into contract with a reputable surveyor to be selected by him, for an amount of work not to exceed $5,000, which is estimated to be the maximum that one surveyor can absorb in a surveying season. No sub-letting of contracts is allowed. This limit can be increased to $8,000, which amount is allowed two surveyors in a *joint* contract.

Should the character of the proposed survey involve the maximum rates, the Surveyor General is required to invite proposals and competitive bids from reliable and experienced surveyors, and advertisements are inserted in local papers, showing the estimated amount and description of the survey. Where the surveyor is unknown to the General Land Office, he is required to file evidence of his qualifications to complete the work.

Where no competitive bids are required, the contracts are prepared and forwarded to the Commissioner of the General Land Office for his approval, but where bids are submitted, they are all sent to the Commissioner by the Surveyor General, with a recommendation as to the lowest bidder.

The Commissioner transmits the bids to the Secretary of the Interior, who alone has authority to allow the increased rates, and after the latter has granted permission to allow the rates and approved the selection of the bidder, the Commissioner instructs the Surveyor General to award the contract. This contract must, however, receive

official sanction by the Commissioner before the work can be entered upon.

Contracts always specify the exact number of miles to be run, and the rates to be allowed for the classes of lines. Of course it is impossible to estimate in advance, how much of the survey will be obstructed and rendered difficult by the lands being heavily timbered, or mountainous, and the complete field notes of the work are necessary to show this.

It will be observed by the practical surveyor that here is an opportunity for impositions to be practiced upon the government, for a line may be returned as exceptionally difficult to survey, when in fact it is unobstructed by any natural obstacles. However, by the system of inspections to be hereafter described, such frauds are detected. Deputies who have been found making false statements as to difficulties encountered or in respect to evidences of surveys are disbarred from future work under the government.

Rates for Contract Surveys.

The payment for surveys made under contract is in accordance with the provisions of annual appropriations by Congress for surveys and resurveys of public lands. The rates are thus fixed by Congressional enactment and do not change from year to year. Surveyors are allowed a compensation by the mile for each mile actually run and marked in the field.

Twenty-five years ago the rates were greater than at present, for obvious reasons. Difficulties attending transportation of supplies and higher prices for provisions and equipment, made the surveyor's profit about equal to the present time.

In fixing the rates, allowance was made for increased difficulties encountered by the surveyor in establishing lines in a mountainous region, and the more important lines requiring greater care to establish were rated higher than subdivisional lines.

There are now nine classes of rates as follows:

Minimum Rates.

For surveys and resurveys of lands offering no obstruction to the surveyor, such as in prairie country.

$5.00 per mile for section lines.
7.00 per mile for township lines.
9.00 per mile for standard and meander lines.

FIG. 1. — U. S. DEPUTY SURVEYOR.
Showing bearing tree and quarter-section post.

Intermediate Rates.

For surveys and resurveys of lands heavily timbered, mountainous, or covered with dense undergrowth.

$7.00 per mile for section lines.
11.00 per mile for township lines.
13.00 per mile for standard, base, and meander lines.

Maximum Rates.

For surveys and resurveys of lands exceptionally difficult to survey where the intermediate rates can not be contracted for.

$12.00 per mile for section lines.
15.00 per mile for township and range lines.
18.00 per mile for standard, base, and meander lines.

Special Maximum Rates.

Allowed only in States and Territories west of and embracing the Rocky Mountains, for the survey and resurvey of lands heavily timbered, mountainous, or covered with dense undergrowth.

$20.00 per mile for section lines.
23.00 per mile for township lines.
25.00 per mile for standard, base, and meander lines.

The above presents a good idea of the grading of the rates paid contractors.

In certain States, such as California, surveys may be contracted for at a *per diem* compensation, the contract fixing the limit of the liability. This is to provide for surveys which cannot be contracted for at the mileage rates, such as small groups of surveys remote from lines of travel. Contracts are made for such work at $25.00 to $40.00 per day, the total cost not to exceed a certain sum.

Corner Monuments.

There are over one hundred varieties of corners prescribed for marking the lines of public land surveys. This seems at first glance to be a rather cumbrous system, but it is the result of an attempt to differentiate the classes of lines and to conform to the conditions found upon the tract surveyed, the desiderata being to plant the most durable monuments without imposing upon the government the cost of transporting materials over great distances.

The great variety is accounted for as follows:

The surveyor is required to establish one of eight kinds of corners, varying according to the character of the ground, and the practicability of securing materials at the points determined, viz.:

First, the *stone corner with pits and mound of earth.* This corner is placed in a cleared space where the earth can be removed.

Second, the *stone corner with mound of stone.* This is placed in open country, in rocky soil where pits are impracticable.

When the point for corner comes in timber, the

Third kind is established: a *stone with bearing trees.*

This corner is considered the best and most durable of all corners. In regions where stone does not abound there is placed the

Fourth kind of corner, which is a *post with pits and mound of earth*, placed in open spaces, but, if corner point come in timber, there is placed the

Fifth kind: a *post with bearing trees.*

If, however, nothing is obtainable with which to make suitable post, and the surveyor is unable to ship to the point proper material, he is allowed to establish the

Sixth kind: a *mound of earth with deposit and stake in pit.*

This corner is considered to be inferior to any other, as its perpetuity is dependent upon its memorials placed under the mound and the small stake in pit. It sometimes happens that a tree is found at the precise point for corner, in which case the

Seventh kind is established. That is, the tree is marked and suitably witnessed by pits and mound of earth, and if the tree is in the midst of others, the

Eighth kind of corner is established, involving the marking of bearing trees.

Differentiation of Corners.

The above described corners comprise those which must be built contingent upon prescribed conditions; they are easily remembered and involve no complications, but the surveyor has something more to learn beside the marking, size, shape, and limits of the above; he must *vary these corners* according to the class of lines he is engaged upon surveying.

There are thirteen classes of corners which govern the kind of monuments. They are:

Standard township corners.
Closing township corners.
Corners common to four townships.
Corners common to two townships.
Corners referring to one township.
Meander corners.

Standard section corners.
Closing section corners.
Corners common to four sections.
Corners common to two sections.
Corners referring to one section.
Quarter section corners.

Reservation corners.

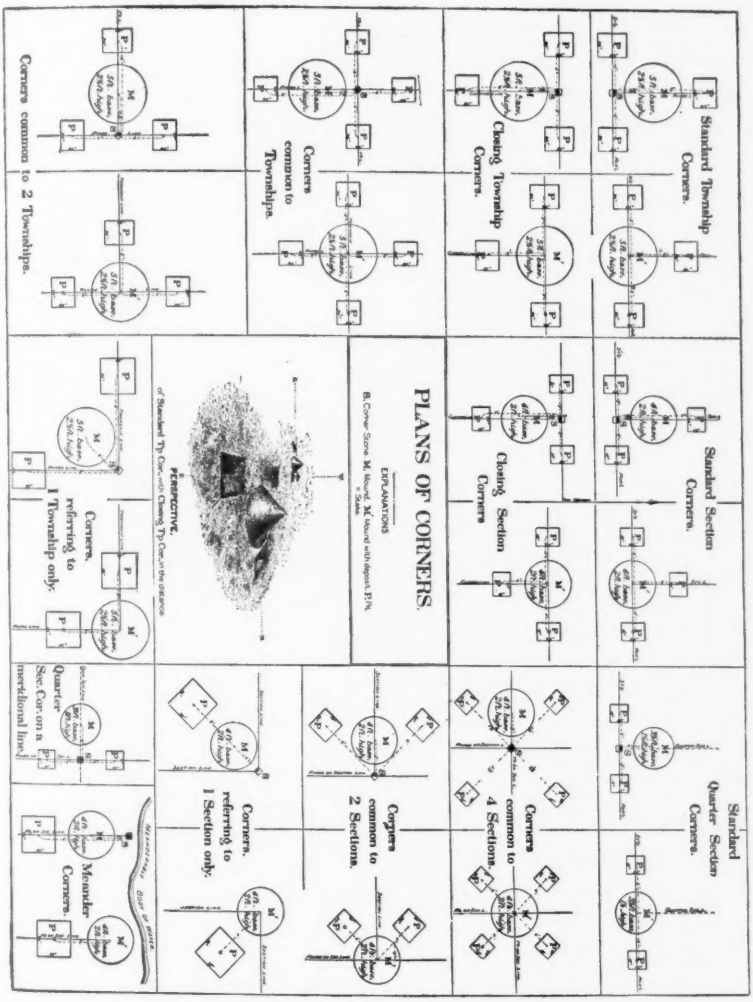

FIG. 2.—GROUND PLANS OF CORNERS OF U. S. PUBLIC LAND SURVEYS.

Now if each monument must have an appropriate size and shape, and the pits be placed differently for each one of the thirteen classes, it follows that the surveyor must be familiar with the construction of 104 kinds of corners in order to be properly equipped for his duties.

In examining candidates for the position of inspector of contract surveys of public lands, it has been found practically impossible to obtain surveyors possessing the necessary qualifications among those who have never been in the field either as deputy surveyors or as chainmen with examiners of surveys.

To young engineers who have in view the undertaking of this kind of surveying I would say, engage as a subordinate in a surveying party for a season and learn thus the conditions peculiar to the work of running lines of public surveys.

Base Lines and Standard Parallels.

It will be at once observed that these lines from which township exteriors are run must be very carefully established, and the instructions and requirements to deputies who attempt such surveys are very full and specific. They must be run as near as possible on a true latitude curve.

If a true meridian be determined at every set up of the solar transit at short intervals, and a right angle be turned, a close approximation to the latitude curve will be attained, but in many cases it is deemed impracticable to pursue this method, and the lines are run by the tangent or secant methods.

Secant Method.

The method of establishing corners on a true latitude curve by offsets from a line situated between and parallel to the chord and tangents was devised to meet the demand for short offsets.

It consists of running out a connected series of straight lines, each 6 miles long, on such courses that any one of the lines will intersect the curve of the parallel of latitude in two points, separated by an interval of 4 miles; and from the lines thus established, measuring north or south, as the case may be, to attain other required points on the latitude curve. The straight lines are called secants.

The direction of the first secant will be determined at its initial point by observation on Polaris, and similar observations are made at

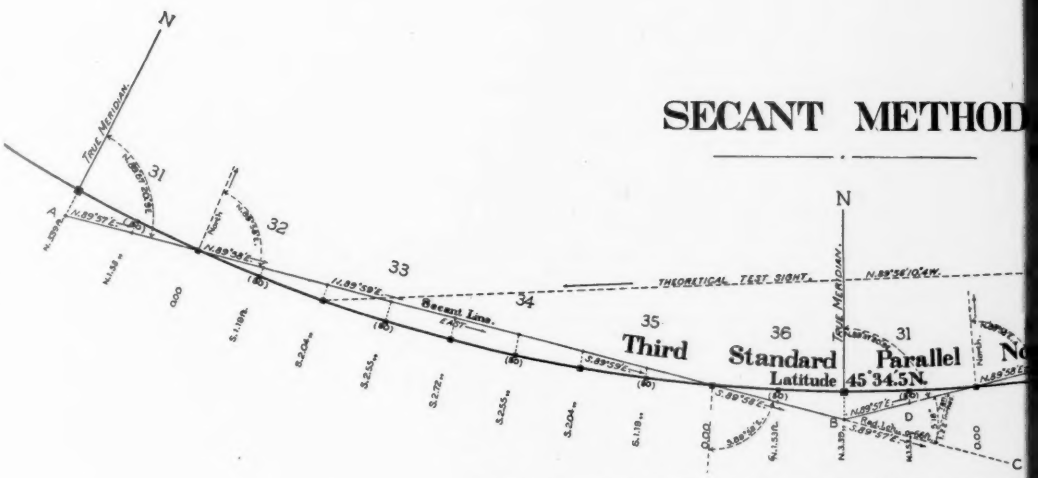

FIG. 3.—SHOWING METHOD OF ESTABLISHING BASE LINES AND

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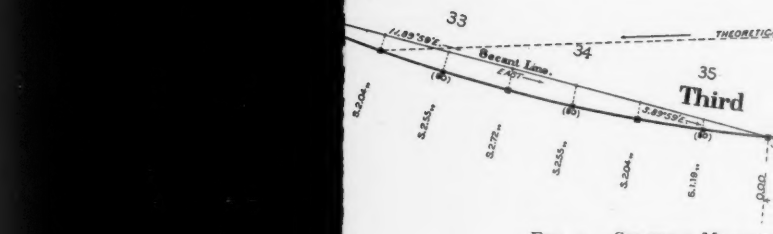
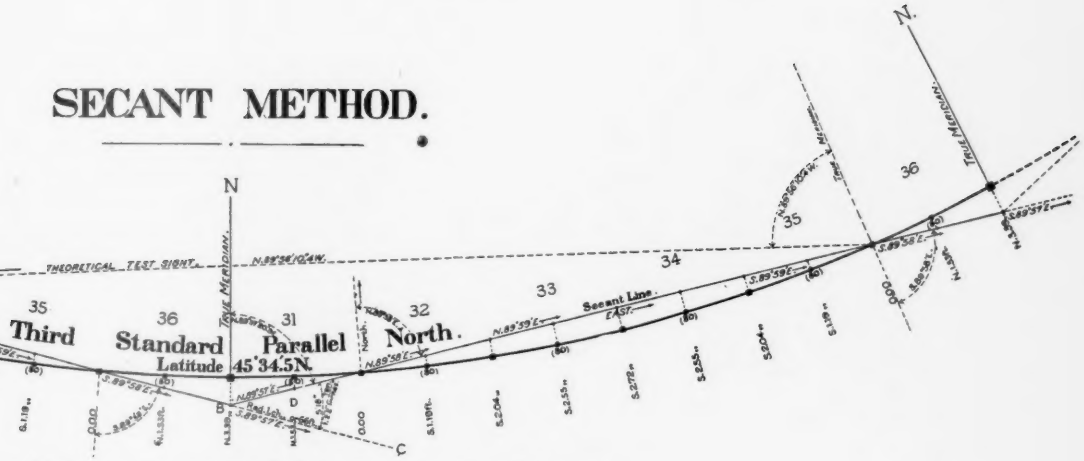


FIG. 3. — SHOWING METHOD

SECANT METHOD.



NG METHOD OF ESTABLISHING BASE LINES AND STANDARD PARALLELS.

intervals of not exceeding 18 miles, while observations are made when practicable every night to guard against mistakes, detect errors, and check the direction of the line. The correct establishment of a standard parallel of offsets from secant lines depends upon:

1. Accuracy of observations on Polaris.
2. Close measurement of the azimuth angle, to define the initial direction of the secant.
3. Careful prolongation of the secant in a straight line.
4. Correct measurement of the deflection angle.

The secant method adapted to transit instruments exclusively, is recommended for its simplicity and accuracy, and the facility with which the line may be extended over rough mountainous land through dense undergrowth; in deep valleys or canyons where the sun cannot be observed in favorable positions, or anywhere during the continuance of adverse weather conditions and under circumstances where the use of solar apparatus would be, if not impossible, at least inconvenient and unreliable.

Tables showing the azimuths of the tangent to the parallel are furnished the surveyor. They are calculated for latitudes 30° to 50° and for each mile point of 12 miles.

Tangent Method.

This method consists in laying off from a true meridian, established by observations on Polaris, an angle of 90° producing the direction thus determined, a distance of 6 miles in a straight line, and measuring north therefrom, at half mile intervals, distances of correct length, taken from tables furnished to deputies for the latitude, to attain other points on the latitude curve passing through the tangential or initial point.

Instruments.

The requirements of the government in the use of instruments in running lines of public land surveys, provide that a solar transit or solar compass shall be employed, and that it shall be run independently of the magnetic needle.

In former times the kind of instrument was not prescribed, and great attention was paid to the variation of the needle. Much literature was furnished bearing upon the diurnal fluctuations of the mag-

netic needle, the annual changes in the magnetic declination and the shifting of the isogonic lines by the lapse of years. Many of the old surveys were executed with the needle compass and the variation either assumed or erroneously calculated. In consequence, the reliability of the surveys was much impaired by reason of local magnetic attraction, the carelessness of deputies, and the consciousness that no field examination would take place.

To avoid this state of things it was resolved to adopt and require the use of an instrument operating by other means than by the needle. Burt's Solar Compass was at first employed, and for twenty years was the only instrument adaptable to finding a meridian by observation upon the sun, which was practicable for field use, and to-day the principles upon which all solar transits used in public land surveying are constructed and the forms of attachments are identical with those of Burt's invention.

By this ingenious contrivance the surveyor can set his compass or transit over any point, and if the sun be shining, he can in five minutes direct his line of sight to a point precisely north or south or east and west of him. All that is necessary for him to know is the approximate latitude and longitude of the place, and the declination of the sun.

Aside from the original Burt's Solar Compass, which is an open sight apparatus, there are several instruments used in public land surveys made by different manufacturers. Gurley & Company use the Jones patent latitude arc, and their telescope carries the declination arc giving the sun's image as in the original Burt's compass. Young & Sons employ an ordinary railroad transit with Smith's Solar Attachment, which consists of an auxiliary telescope carrying a declination arc, and having a counterpoise. The image in this attachment is considerably increased in size, being several times larger than in the Gurley instrument. Keuffel, Esser & Company, manufacture the Saegmüller Solar Attachment to their solar transits.

There are other devices for solar work made as attachments to engineer's transits, which will not be described. Surveyors are divided in their preferences among these instruments, and it is outside the province of this article to write their advantages and disadvantages. The government, however, permits the use of the ordinary transit without any solar equipment whatever, provided the surveyor takes frequent observations for meridian, and in the use of the ordinary

transit, the deputy must observe for meridian each night, or upon the sun by day where practicable, turning off transit angles from his meridian for his east and west lines, making the necessary corrections

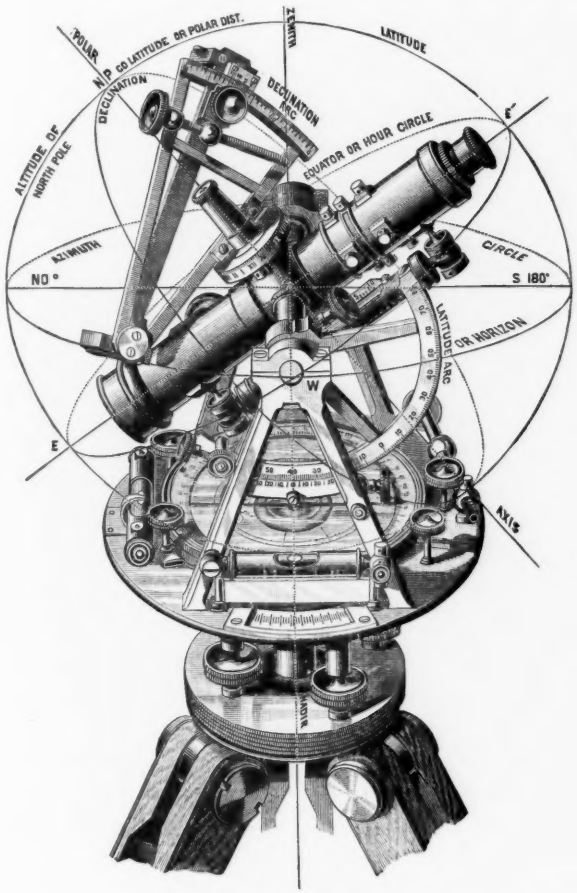


FIG. 4. — A SOLAR TRANSIT.
Showing principles of construction.

and allowances by subsequent observations. Very accurate surveys are made by this method, but the method is not considered by many surveyors to be rapid enough for profitable work.

Meridian Observations.

The work of Government Land Surveys involving true meridian lines makes the ascertainment of the exact direction of a north and south line by the surest and quickest means a great desideratum. The government does not insist upon any one method of finding the stellar meridian, but describes and recommends several methods in the *Manual of Surveying Instructions.*

Among these is the alignment of certain stars when Polaris is in culmination. When the star Zeta of the Great Bear, or the Big Dipper, is in the same vertical plane with the North Star, the latter is on the true meridian. Also when Delta of Cassiopeia and Polaris are in line vertically, a very close approximation to a true meridian is reached. In observing these transits it is necessary to allow a small interval of time to elapse before staking down the meridian.

The well known formula for ascertaining the azimuth of Polaris at elongation is furnished to all deputy surveyors, and they are given tables showing culminations of this star. Employment of this means of securing a meridian involves remaining up often until after midnight, and this to the tired deputy means the loss of much needed sleep.

In order to avoid the inconvenience attending the elongation and culmination method of Polaris observations, a plan was devised by the surveying division of the General Land Office, and tables furnished public land surveyors by which the azimuth of Polaris could be ascertained by direct observation of the star *at any hour when visible.* This was a great boon to the surveyor. It is called the hour angle method.

The hour angle is obtained by subtracting the time of upper culmination from the correct local mean time of observation, and applying the result to a table of azimuths of Polaris. Stellar observations for meridian are almost universally used by surveyors, but there are some deputies (those generally who are running lines by transit without solar attachment) who obtain their meridians by observations upon the sun. This can be accomplished by the following rule:

Add together the polar distance, the latitude, and the true altitude; take the difference between the half sum and the polar distance, and note the remainder. Add together the log. secant of the latitude, the log. secant of the altitude, the log. cosine of the half sum,

FIG. 5. — AN INSPECTION PARTY.
The position of the transit indicates the "falling."

and the log. cosine of the remainder; half the sum of these four logarithms will be the log. cosine of half the true azimuth of the sun.

Determination of the true meridian at intervals is required of deputies for the purpose of testing the accuracy of their solar apparatus, especially after moving camp and subjecting the delicate adjustments of the parts to the inevitable jarring and jolting of travel in rough mountainous regions. Conscientious surveyors will observe for meridian nearly every clear evening in order that observations may check each other. Surveyors are required to note in their records the details of such determinations in order that the General Land Office can ascertain if incorrect methods are employed.

Sometimes government surveyors record the details of an hour angle observation, which show an error of azimuth amounting to several minutes. Such an observation was probably never made, for the reason that, if as they state, their solar is in accord with the meridian as determined by such an amount of azimuth, it could not be in adjustment if the azimuth, as *correctly worked out*, were three or four minutes greater or less.

Inspections.

Prior to the "eighties," public land surveys made under contract were seldom examined in the field before payment, and as a consequence, the temptation to fraud and carelessness was very great. In other branches of the government, supplies for official use furnished by contract are duly inspected by vigilant officers to ascertain if the article be according to specification, but in the matter of surveys, strange to say, surveyors were formerly permitted to make returns to the Surveyors General of their work, their oath and that of their assistants being deemed sufficient guarantees of its correctness. But as the country became settled it was apparent that in many instances gross frauds had been perpetrated by unprincipled deputies and the government had paid for mere "paper" surveys; besides in numerous cases inaccurate lines were established, although the monuments were reasonably well marked.

To remedy this, the Surveyors General were instructed to make such inspections as they thought proper by men selected by them and to allow them full equipment of men and supplies to take the field and examine portions of the contract. These inspectors were generally other deputies, and they were naturally loth to find errors in each

other's work. Their reports were usually favorable, and it was rare to have one of these reports show gross neglect of duty on the part of the deputy.

As the work did not seem to grow more in accordance with the required standard, a new departure was determined upon.

A corps of Examiners of Surveys was appointed to consist of experienced engineers and practical surveyors, operating in conjunction with expert public land surveyors detailed from the surveying division of the General Land Office. These examiners comprise a trained class of men who are directed by the Commissioner, and are independent of any local affiliation or sympathy. They report their findings to the Commissioner, and upon their statements he accepts or rejects the surveys. This method has been in vogue for several years and correct and faithfully executed surveys are the result.

Surveys in Newly Acquired Territory.

It will doubtless be asked if the system will be extended to the outlying territories recently added to the United States.

In the case of Alaska, the last Congress extended the system to that district, but not being contiguous to the "States," the lines can not well be prolonged to embrace the lands desired to be surveyed, and if the survey of tracts of agricultural land be applied for by settlers, independent base and meridian lines will probably be established to govern the surveys, as the mountainous character of the surface of Alaska will preclude the possibility of a connected system over the entire country.

In Hawaii the commission appointed to recommend a form of government has advised the appointment of an officer whose functions shall be similar to those of our Surveyors General, to take charge of government surveys of what is known as "crown lands."

In Cuba, Porto Rico, and the Philippines, should there be found considerable areas of crown lands subject to disposal by the United States, the survey of such lands will unquestionably be proceeded with in the same manner as are lands in the public land States.

Reforms.

It would be natural to expect that in the course of years, modifications and improvements of the system would be suggested by experience. One of the changes which may be recommended to Congress

is the use of tubular iron posts, capped with brass, copper, or steel, upon which are to be stamped the data now placed upon the corner stones or posts. These would be more durable and less likely to be removed or destroyed by fire. They would be flanged at bottom and tamped, securing a rigidity not obtainable by the wooden post now in use.

Another change in the law, which is in the interest of promptness and accuracy, is the adoption of a proviso authorizing the contracting for small fragmentary surveys such as islands, for a lump sum. The law provides now that surveys however insignificant, involving sometimes a fraction of a mile, must be paid for at mileage rates, which results in the failure to find competent surveyors who are willing to go to the expense of traveling, oftentimes many miles, to a remote locality and receive three or four dollars as compensation for their work.

Still another progressive step would be the accomplishment of a topographical, or contour, survey simultaneously with the public land survey, such as has been done by the United States Geological Survey. This may be done by increasing the contract rates to cover the cost of topographical survey equipment.

Other and less important changes in the rules for public land surveying have been considered and adopted from time to time by the General Land Office, in cases where no Congressional authority is required. Their enumeration would materially lengthen this article, which is only intended as a brief exposition of the system.

ON THE NECESSITY OF CULTIVATING WATER BACTERIA IN AN ATMOSPHERE SATURATED WITH MOISTURE.

By GEORGE C. WHIPPLE, S. B.

According to present practice the number of bacteria in a sample of water is found by mixing a certain quantity of the water with a certain quantity of sterilized nutrient gelatin and allowing the mixture to solidify in a Petri dish. After a longer or shorter period of incubation at a temperature at or about 20° C., the colonies that have developed upon the gelatin are counted, and from this count the number of bacteria present in the water is determined. Although this method is almost universally used, and although the results obtained are sometimes of the greatest moment, there is such a lack of uniformity in the details of the process as ordinarily conducted, that the determinations of different observers are seldom comparable unless the methods of procedure are fully described. A standard method of procedure is urgently needed, but cannot be secured until the various factors that influence the result have been analyzed and their magnitude determined. In the course of a series of experiments conducted with this object in view, it was observed that the amount of moisture in the atmosphere of the incubator exercised an important influence upon the number of bacteria that developed. The results of these observations are summarized in this paper.

Before the use of the Petri dish it was customary to pour the mixed gelatin and water upon a cold glass plate, where it was allowed to spread out and harden. The plate was then covered with a bell-jar and put in the incubator. In order to prevent the gelatin from drying, moist filter paper was put at the bottom of the bell-jar. Thus the bacteria developed in a moist atmosphere. With the advent of the Petri dish the matter of moisture seems to have been lost sight of. This dish was provided with a tight fitting cover, and this was supposed to prevent evaporation from the gelatin. It is a fact, however, that the Petri dishes now on the market are not tight, and that often the covers

fit the plates very badly. Furthermore, in laboratories where many dishes are in daily use, it is a common thing for dishes and covers to be mismated, and often there is no attempt to mate them. The result is that an appreciable evaporation from the gelatin does take place, and that the amount of evaporation varies with different plates and with different atmospheric conditions.

The effect which this uncontrolled factor exercises upon the development of bacteria is shown by the following experiments. Several series of cultures were submitted to varying conditions of moisture, with other conditions remaining constant. The plates were incubated in a moist chamber, in a closed chamber without moisture, in the incubator (or the ice chest), and in a desiccator. For the moist chamber a desiccator-jar was used, the sulphuric acid being replaced by water. The closed chamber was a desiccator-jar without sulphuric acid or water. The jars were large enough to hold five plates, and in all cases the figures representing the numbers of bacteria found were obtained from the averages of the five counts. The results are given in the following tables. Table I shows the average number of bacteria that developed upon each set of plates. In Table II these figures are reduced to percentages of the number that developed in the moist chamber.

TABLE I.

Series.	Date.	Period of incubation. (Hours.)	Temperature of incubation. (Centigrade.)	Number of Bacteria Per Cubic Centimeter.				
				In moist chamber.	In ice chest.	In incubator.	In closed chamber.	In desiccator.
	1899.							
A.	July 7.	96	16°	583	527	—	—	465
B.	July 7.	96	16°	507	430	—	—	415
C.	July 7.	96	16°	750	683	—	—	618
D.	Oct. 9.	96	15°	450	438	—	395	342
E.	May 20.	72	18°	154	—	115	—	111
F.	Oct. 14.	72	20°	108	—	89	90	84
G.	Oct. 9.	48	20°	423	—	413	354	324
H.	Oct. 17.	72	20°	61	—	59	—	51

TABLE II.

Series.	Date.	Period of incubation. (Hours.)	Temperature of incubation. (Centigrade.)	Per Cent. which Each Number was of the Number Found in the Moist Chamber.				
				In moist chamber.	In ice chest.	In incubator.	In closed chamber.	In desiccator.
	1899.							
A.	July 7.	96	16°	100	90	—	—	79
B.	July 7.	96	16°	100	85	—	—	82
C.	July 7.	96	16°	100	91	—	—	82
D.	Oct. 9.	96	15°	100	98	—	88	79
E.	May 20.	72	18°	100	—	75	—	73
F.	Oct. 14.	72	20°	100	—	82	83	77
G.	Oct. 9.	48	20°	100	—	98	83	77
H.	Oct. 17.	72	20°	100	—	97	—	83
Average.	.....	..	..	100	91	88	85	78

From these tables it will be seen that the largest numbers of bacteria were always obtained from the plates that developed in the moist chamber, and that the smallest numbers were always obtained from the plates that were kept in the desiccator. If the number that developed in the moist atmosphere be assumed to represent the maximum number obtainable by the method, it follows that only 78 per cent. of the bacteria developed in the desiccator, that 85 per cent. developed in the closed chamber, and that the numbers that developed in the ordinary incubator and in the ice chest varied from 75 per cent. to 98 per cent. There was a striking uniformity in the percentages which the numbers in the desiccator were of the numbers in the moist chamber and this was due, no doubt, to the constant atmospheric conditions in the two jars. In the closed chamber also the percentages were quite constant. In the ice chest and in the incubator the percentages were more variable. The atmosphere of the ice chest was ordinarily more moist than that of the incubator, but was seldom saturated on account of ventilation. The amount of moisture in the air of the incubator was generally greater than that of the atmosphere of the laboratory, and varied more or less with the ventilation, the number of plates kept in the incubator, etc. In Series E the relative humidity

of the atmosphere in the incubator was estimated at about 60 per cent. In Series F the humidity was determined by hourly readings of a psychrometer and was found to vary between 65 per cent. and 80 per cent., the average being 75 per cent. In Series G the atmosphere of the incubator was kept moist by means of jars of water, and the average humidity was 95 per cent. In Series H the humidity was similarly kept at 98 per cent. of saturation. The relation between the humidity and the development of bacteria is shown by the following comparison:

Series.	Relative Humidity of the Atmosphere of the Incubator in per cent. of Saturation.	Per cent. which the Number of Bacteria that Developed in the Incubator was of the Number that Developed in the Moist Chamber.
E.	60 (estimated.)	75
F.	75	82
G.	95	98
H.	98	97

The amount of evaporation from gelatin under the conditions described above was determined by weighing the dishes with their contents before and after incubation. It was found that in a saturated atmosphere the evaporation was inappreciable; in the closed chamber it was from 1 to 2 per cent. of the weight of the mixed water and gelatin during 72 hours; in the ice chest it was about 3 per cent.; in the incubator it was from 3 per cent. to 5 per cent.; and in the desiccator it was from 10 per cent. to 15 per cent. The amount of evaporation varied greatly with different plates submitted to the same conditions.

This loss of water by evaporation is sufficient to cause important changes in the composition of the culture media during incubation, and this may be sufficient to affect the development of the bacteria, as these organisms are very susceptible to slight changes in environment. But the chief reason why increased evaporation is accompanied by a decrease in the percentage of bacteria that develop seems to be connected with the supply of oxygen. By successive weighing of the same plates it was found that the rate of evaporation was not constant, but decreased rapidly. For example, during the first hour

of incubation the evaporation from a series of plates proceeded at the rate of .068 gram per hour; after 18 hours the rate of evaporation was .031 gram per hour; after 42 hours it was .012 gram per hour, and after 96 hours it was .002 gram per hour. This retardation of the rate of evaporation appears to be due to a thickening of the gelatin at the surface. If such is the case, the thickened gelatin at the surface might materially reduce the supply of oxygen of the submerged bacteria and prevent the development of the less vigorous aërobic forms. Indeed, it was observed that the plates in the desiccator and in the moist chamber differed more in the number of submerged colonies than in the number of surface colonies.

These facts suggested the possibility that the Petri dish itself might serve to prevent the bacteria from getting a sufficient supply of oxygen. The experiment was made, therefore, of cultivating the bacteria in a Petri dish with the ordinary cover replaced by a ground glass top that made an absolutely air tight joint. A series of five cultivations made in this way gave the number of bacteria in a certain sample as 317 per cc., while a series of cultivations of the same water made in the usual manner gave 413 per cc. In the hermetically sealed dish, therefore, only 77 per cent of the bacteria developed. The air of these dishes was then collected over mercury, and the amount of oxygen determined by absorption with pyrogallic acid. It was found that the air of the ordinary dishes contained approximately 15 per cent. of oxygen, while the air of the sealed dishes contained only 5 per cent. In other words, three-quarters of the original supply of oxygen in the sealed dishes had been used up by the bacteria during 72 hours, while one-quarter of the original supply had been used up in the ordinary dishes. It was found also that the air in the sealed dishes contained 5 per cent. of CO_2, while the air in the ordinary dishes contained but 2 per cent.

As a matter of interest a series of cultures was made in a jar filled with oxygen, and compared with cultures of the same water made in the incubator. It was found that the average number of colonies that developed in the oxygen was 154 per cc., while in the incubator it was 137. The growth in oxygen also took place at a much more rapid rate.

Finally, one important fact was noted in connection with the cultures made in the jars that illustrates the important effect of oxygen. In all the jars the five Petri dishes were piled one on top of the other,

and it was found that almost invariably the plate highest in the jar gave the largest count, and that the lowest plate gave the smallest count. This was particularly striking in the case of the jar filled with oxygen, where the upper plate contained 198 colonies per cc., while the lower plate contained 138. These differences between the upper and lower plates of the jars were greater than the differences observed between plates kept in the incubator. Liquefaction proceeded much more rapidly in the upper plates of the jars. These phenomena seemed to be due to an accumulation of carbon dioxide at the bottom of the jars, where either by its own properties or by exclusion of oxygen, it retarded the growth of the bacteria.

These facts tended to show that the supply of oxygen has a marked effect upon the growth of water bacteria on the gelatin plate, and that whatever tends to reduce the supply of oxygen, whether it be evaporation or an air-tight Petri dish or lack of sufficient ventilation, will tend also to reduce the number of bacteria. The practical inference from this is that in order to obtain the greatest possible development of water bacteria on the gelatin plate, a ventilated dish should be used, and the cultures should be incubated in an atmosphere saturated with moisture.

It has been found that satisfactory ventilation of the Petri dishes may be obtained by grinding several small notches in the edge of the lower plate. If greater ventilation is required, it may be obtained by extending the sides of the lower plate upwards at four points on the circumference so as to form pillars for supporting the cover, thereby allowing a complete circulation of air. It has been found that the bacteria counts obtained by using these ventilated dishes in an atmosphere saturated with moisture, compare closely with those obtained in open dishes protected from contamination and incubated in a saturated atmosphere, the results of one series of comparisons giving 97 and 95 bacteria per cc. respectively, by the two methods. Experiments have shown that there is no danger of these ventilated plates becoming contaminated from the air.

The cultivation of water bacteria in the moist atmosphere has the further advantage that the growths come to maturity in a shorter time. Liquefaction takes place earlier, but the growth of the deep-seated colonies seems to proceed at a still more rapid rate. A greater proportion of the plates are liquefied after 72 hours' growth, but on the other hand, the percentage increase between the 48-hour count and the 72-hour count is much reduced.

Incubators used for the cultivation of water bacteria should be well ventilated, and their atmosphere should be kept at or near the point of saturation. They should be provided with wet and dry bulb thermometers, and the relative humidity should not be allowed to fall below 95 per cent. Experience has shown that an atmosphere practically saturated with moisture may be easily maintained.

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SILICA STANDARDS FOR THE DETERMINATION OF TURBIDITY IN WATER.

By GEORGE C. WHIPPLE, S.B., and DANIEL D. JACKSON, S.B.

The subject of the turbidity of water is one that is growing in importance. This importance varies in different sections of the country. In New England, where the natural waters are comparatively clear, the terms "very slight," "slight," "distinct," and "decided," have been used by analysts to express the amount of suspended matter present. These degrees of turbidity have been estimated by the appearance of the samples to the eye when viewed towards the light. This mode of expression has been discarded by analysts who have had to deal with the problem of turbidity in connection with sand filtration or the mechanical treatment of waters that have large quantities of clay and other foreign matter in suspension. Experiments have shown that it is the finely divided suspended matter in water that is most difficult to remove by any system of purification, and it happens that these same fine particles have the greatest effect on the turbidity of the water. Hence, in questions relating to the filtration of water, the amount of coagulant required for clarification, etc., a reliable expression for the actual turbidity is more serviceable to the engineer than a knowledge of the exact weight of the suspended matter. Consequently indefinite terms have been discarded and more accurate systems of numerical expression have come into use.

Of the various methods that have been suggested, only three have commended themselves to practical use: namely, the Wire Method, the Diaphanometer, and the use of Standards of Comparison. The first is a rapid method for obtaining approximate results, and serves well as a local standard and for the general purposes of field work, but it is not applicable to laboratory use. The second requires a somewhat elaborate apparatus and conditions of observation not readily obtainable in all laboratories. The third method is simple and quite satisfactory for general use. Standards of kaolin have been used for this purpose, but they are open to the objections that they cannot be

readily duplicated and do not keep well when employed in connection with the color standard. These difficulties appear to be overcome by the use of finely powdered diatomaceous earth instead of kaolin. This earth may be obtained in almost any part of the country, and is prepared for use in the following manner:

The diatomaceous earth, as pure as may be obtained, is washed with water to free it from any soluble salts, and ignited to remove the organic matter. The perfectly white earth thus obtained is then treated with warm hydrochloric acid (1 : 1), after which it is washed with distilled water by successive decantations until free from the acid. The material, now composed of practically pure diatom frustules is then ground in an agate mortar to an impalpable powder and again shaken with distilled water. Any coarse particles that may be present are easily separated from the fine particles by sedimentation and decantation. The fine material is then allowed to settle, separated from the water, dried at 100° C., cooled in a desiccator, and placed in a stoppered bottle. The material thus prepared for use consists of particles of silica that are about 1 micron (.001 mm.) in diameter, and that are fairly uniform in size.

A stock mixture is made by adding 0.5 gram of the prepared diatomaceous earth to 500 cc. of distilled water. This is put in a liter bottle in order to give room for violent agitation before measured portions of it are withdrawn. The mixture contains 1 gram of pure silica per liter, or 1,000 parts per million. This is absolutely unacted upon, either by distilled water or by the platinum-cobalt color standard, and when well shaken will always give the same turbidity.

For waters of low turbidities, standards are made up in gallon bottles. The stock mixture above described is called a standard of 1,000. Five standards are made from this by dilution, as follows:

Silica standard.	Number of cubic centimeters of stock mixture, to be made up to 3 liters with distilled water.
0	0
5	15
10	30
15	45
20	60

Nearly all of the natural waters of New England fall below the standard of twenty. These comparatively clear waters may be examined by putting them in gallon bottles like those holding the standards,

and viewing them together towards the light. It is well to have under the bottles a black surface that extends backward for about 1 foot, rising at an angle of about 30°. This enables the observer to distinguish the particles in suspension, to judge the amount of light that they cut out, and to estimate the turbidities even though the particles vary greatly in size.

The numerical expressions given in the following table may be considered as the approximate equivalents of the terms now employed for expressing low turbidities.

Silica standard.	Present system.
0	None.
1 — 2	Very slight.
2 — 5	Slight.
5 — 20	Distinct.
above 20	Decided.

Low turbidities observed in this manner are not appreciably interfered with by the color of the water, and consequently the color standards need not be used in connection with the turbidity standards. But above a turbidity of twenty the water in the gallon bottles is too opaque to make satisfactory comparisons, and it becomes necessary to resort to the use of 100 cc. tubes. (Nessler jars about 20 mm. in diameter and 280 mm. long are preferable for this purpose, but the shorter form of 100 cc. Nessler tubes may be used.) A series of twelve standards is made by diluting the stock mixture to the 100 cc. mark, as follows:

Silica standard.	Number of cubic centimeters of stock mixture, to be made up to 100 cc. with distilled water.
20	2.0
30	3.0
40	4.0
50	5.0
75	7.5
100	10.0
125	12.5
150	15.0
175	17.5
200	20.0
250	25.0
300	30.0

When the turbidities are low, the samples may be compared with the standards by holding both over sharp black lines on white paper, and looking through the tubes lengthwise. They may be compared also by examining them sidewise towards the light or over black lines, thus largely eliminating the effect of color. The higher standards are opaque when viewed lengthwise, and must be examined sidewise towards the light, or over black lines at an angle with the light. During the comparison of the water with the standards, the tubes must be shaken occasionally in order to keep all the material in suspension. The stoppers used in the tubes should be boiled in water before they are used, in order to extract any natural coloring matter which they may contain. Waters that have both a high color and a high turbidity may be compared with standards made by combining the silica standards with the platinum-cobalt color standards. The color of the water is first determined by filtering the sample, and the turbidity then observed by comparing the original water with silica standards made to have the same or nearly the same color.

Various river waters recently examined have shown turbidity-readings up to 3,000 of the silica standard, and some of them have had also a high color. It was found that the turbidity of these waters could be accurately determined by dilution of the samples to bring them within the range of the series above described. In most cases this dilution with distilled water entirely eliminated the effect of color. It is only in cases of especially high color and where great accuracy is required that it will be necessary to use the combined color and turbidity standards. In those cases where the suspended particles themselves are colored, sufficient dilution will overcome the difficulty.

The relative value of silica and kaolin for turbidity standards is shown by the following comparisons: Three samples of kaolin were obtained from different sources and standards made from each by adding equal weights of the material prepared by elutriation, to the same volume of water. The resulting turbidities were far from uniform, as shown by the following comparisons with the silica standard.

	Turbidity.
Silica	100
First sample of kaolin	125
Second sample of kaolin	135
Third sample of kaolin	220

Different preparations of silica from diatomaceous earth on the other hand, gave practically uniform results. Microscopical examination of the silica and kaolins showed that the particles of silica obtained by grinding the diatomaceous earth were quite uniform in size, while the particles of aluminum silicate showed much greater variations. In some of the samples the kaolin particles were much finer than in others, which accounted for the great variations in turbidity in the different samples of kaolin.

The silica method of determining turbidity has been employed with a large number of waters, in which nearly every form of turbidity has been represented, and as a general laboratory method it commends itself for simplicity, uniformity, and accuracy.

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GEOLOGICAL HISTORY OF THE NASHUA VALLEY DURING THE TERTIARY AND QUATERNARY PERIODS.[1]

By W. O. CROSBY.

Introduction.

The Nashua holds a unique place among the rivers of New England, inasmuch as it is the largest stream east of the Hudson and the Champlain Valley, flowing throughout the main part of its course in a northerly direction. Its only real competitors are the distant Hoosac and the neighboring Concord. The Hoosac holds its northward course only for some fifteen miles from its source and is, therefore, relatively insignificant; and the Concord is not only a smaller stream than the Nashua, but it is virtually a river without a well accentuated rock valley, meandering across a drift-covered peneplain from an almost imperceptible southern water-parting, seemingly but little influenced by the geological structure of the region.

The Nashua, on the other hand, flows through a deep and well-defined valley which has been carved out of a great slate formation between the mountainous and semi-mountainous Wachusett-Watatic ridge of granitic and gneissic rocks on the west, and a distinct ridge of granitic rocks and schists on the east. This eastern ridge, though in no sense mountainous, is sufficiently prominent so that it has been credited with climatic influence, protecting the Nashua Valley from the chilling east winds and fogs of the coast. This deep northward draining valley presents ideal conditions for the study of the phenomena of glacial lakes, and probably nowhere in New England was this phase of the closing stage of the Pleistocene ice-sheet more typically

[1] This paper is designed to supplement that on the "Geology of the Wachusett Dam and Wachusett Aqueduct Tunnel of the Metropolitan Water Works in the vicinity of Clinton, Massachusetts," in the *Technology Quarterly* for June, 1899, (Vol. XII, 68–96.) My official connection with the Metropolitan Water Board, as consulting geologist, has afforded me exceptionally favorable opportunities to make this study; and my grateful acknowledgments are again due the Metropolitan Water Board and Mr. F. P. Stearns, the Chief Engineer of the Board, for encouragement in the prosecution of this work and for permission to publish the results of special geological interest. It is also a pleasure to acknowledge the unfailing kindness of Mr. H. A. Miller and Mr. T. F. Richardson, Department Engineers of the Board, and of other members of the Engineering Staff.

developed. One main purpose of this paper is to describe the chief episodes in the history of the glacial lake Nashua. The glacial history of the Nashua Valley undoubtedly affords an explanation of the marked retrograde course of the Nashua River with reference to the Merrimac, north of Ayer, and of the retrograde courses of the principal tributaries of the Nashua itself.

Although, for the reasons indicated, the Nashua Valley presents naturally a very attractive field for the student of glacial geology, it is rendered doubly inviting at the present time by the operations of the Metropolitan Water Board in the construction of the great reservoir required for the proposed addition to the water supply of the Metropolitan District. This reservoir, with an area of six and one-half square miles and a maximum depth of 129 feet, will reproduce in part the glacial lake which once adorned the upper valley of the Nashua, and the preparations for the advent of the former have brought to light some of the more important and significant facts in the history of the latter, and of the Nashua River.

Topography.

Two peneplains are readily recognized in this part of New England. In the order of their development these are: First, the Cretaceous peneplain, with a normal elevation of 1,000 to 1,200 feet in central Massachusetts and gradually increasing in height northward and westward. Since it is from the surface of this peneplain that the mountains of the region, such as Wachusett, Watatic, Monadnock, etc., (erosion-remnants, or monadnocks, of a still more ancient land which was base-levelled in Cretaceous times to form this peneplain) immediately arise, it may also be appropriately designated the sub-mountainous or piedmont peneplain. Second, the Tertiary peneplain, with a normal elevation of 100 to 200 feet, and gradually increasing in height from the shore inland toward the somewhat abrupt margin of the piedmont peneplain, which has been worn away in the development of this lower or coastal peneplain, from the surface of which numerous isolated remnants of the older peneplain now rise as monadnocks, including the Blue Hills, Prospect, Nobscot and Fay Hills, and many others.

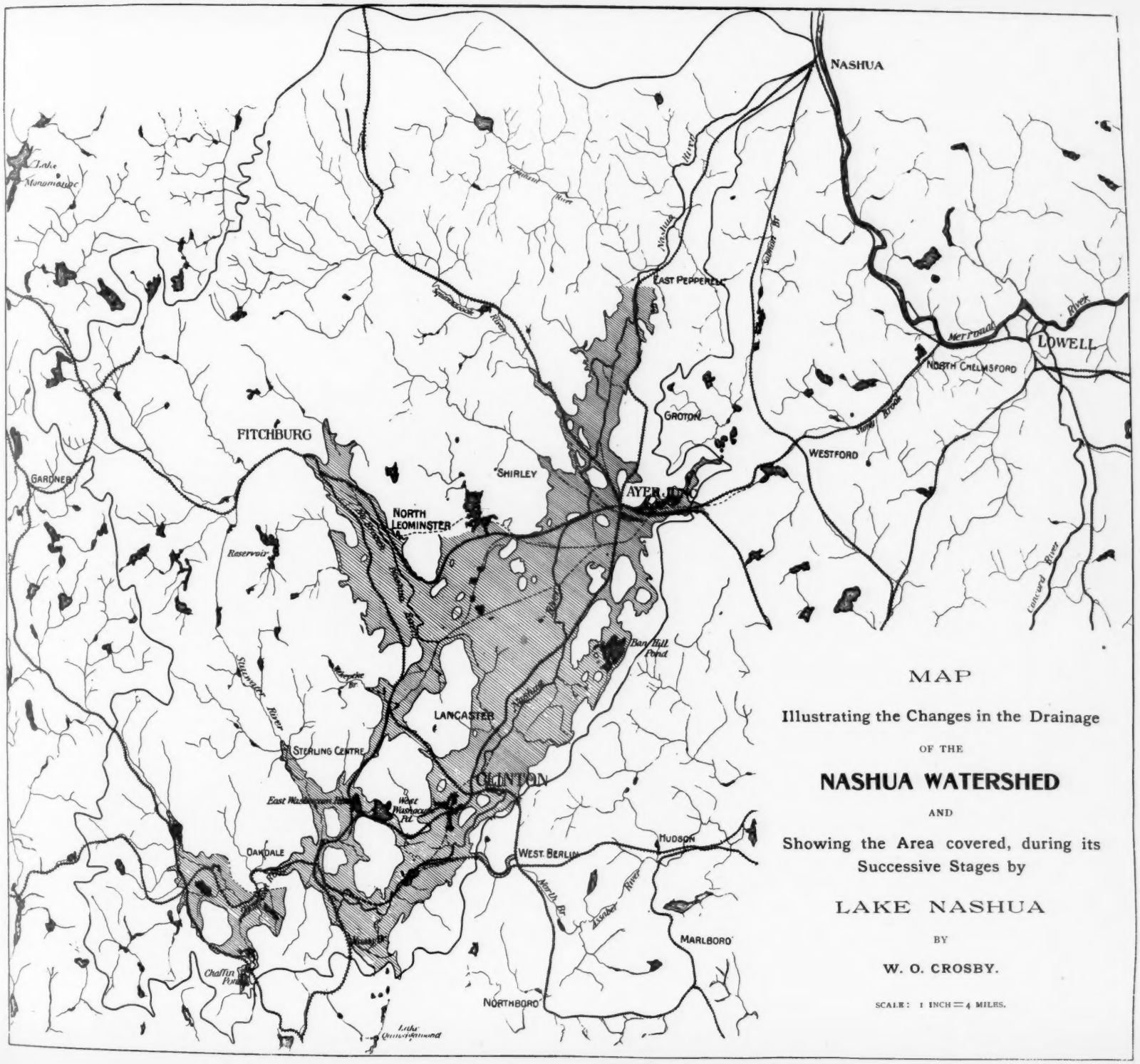
The piedmont peneplain is now broadly divided by the Connecticut Valley, the level floor of which is but an inland extension on a belt of

soft rocks (sandstones and shales) of the coastal peneplain. This statement may be repeated for the Merrimac Valley and for its tributary in which we are now specially interested — the Nashua Valley. The coastal peneplain of Eastern Massachusetts is continuous inland with the floor of the Nashua Valley which, as previously noted, has been developed in a band of relatively soft argillaceous strata. The Nashua Valley is, then, a broad and deep trench which has been excavated in the piedmont peneplain adjacent to and parallel with its abrupt eastern margin, in conformity with the geological structure, and contemporaneously with the development of the coastal peneplain, of which its floor is an inland extension.

The drainage of this region is determined by the normal seaward slope of the peneplains, where uninfluenced by the geological structure. The prevailing line of strike in the region of the Nashua Valley is north-northeast, or approximately at right angles to the dominant inclination of the cretaceous or piedmont peneplain; and the Nashua Valley as it now exists, with its floor of argillites and phyllites or semi-metamorphic slates, is due to the fact that the free eastward drainage from the Wachusett-Watatic height of land is intercepted by the band of granitic rocks (granite and diorite) and highly metamorphic sediments (schists, quartzite, and conglomerate) forming the eastern rim of the valley. The Nashua thus, by virtue of the rugged and semi-mountainous topography, shows itself less indifferent to the geological structure of its bed rocks than do most of the streams of southeastern New England.

This view of the geological relations of the Nashua, namely, that the drainage has been controlled by a band of hard rocks, explains not only the close agreement of the trend of the valley and of the main stream with the strike of the rock formations, but also the sharply defined character of the eastern ridge, and the facts that the river follows closely the western base of this ridge, instead of meandering through the middle of its broad valley, that the tributaries are distinctly transgressive, and that all those more than a mile or two in length join the main stream from the west.

The valley of the Nashua is an approximately rectangular depression with a north-northeast trend, excavated in the submountainous peneplain near its eastern edge. The extreme length of the valley, from Stone House Hill in Holden (four miles northwest of Worcester) to the confluence of the Nashua and Merrimac, is about 40 miles;



MAP

Illustrating the Changes in the Drainage

OF THE

NASHUA WATERSHED

AND

Showing the Area covered, during its Successive Stages by

LAKE NASHUA

BY

W. O. CROSBY.

SCALE: 1 INCH = 4 MILES.

but the extreme length of the river, measured from the source of either the North or South Nashua, and omitting meanders, is about 55 miles. The breadth of the valley is approximately uniform and roughly one-third to one-half its length, being 13 miles across the southern end, 14 miles at Clinton, 16 miles at Mt. Wachusett, 17 miles at Pepperell, 16 miles at the State line, and 17 miles at the north end. The extreme breadth, however, is over 20 miles along the line passing through Ayer and Fitchburg, and the total area is about 516 square miles. The axis of the depression (the course of the main stream) as previously noted, lies near the lower eastern margin, giving the valley its highly unsymmetrical cross section.

The Nashua crosses the 400 feet contour at Oakdale; the 300 feet contour at the mouth of Muddy Brook, in Boylston; the 200 feet contour in Groton; and the elevation of the Merrimac at the mouth of the Nashua is about 100 feet. The average fall of the river is thus nearly 10 feet per mile, affording ample water power; and the distribution of the fall is more definitely indicated by the manufacturing towns on its banks. The fall between Oakdale and Boylston is over 100 feet; in the vicinity of Clinton and Lancaster, about 50 feet; at Groton and Pepperell, over 50 feet; and near Nashua, 75 feet. At most points south of Ayer the river lies from 300 to 400 feet below the eastern rim of the valley, or 800 to 1,000 feet or more below the distant western rim. On the 600 feet contour, the valley south of Ayer is only from 3 to 6 miles wide; and the 500 feet contour gives an approximately symmetrical profile, with the river in the middle.

In the glacial history of the Nashua Valley, the depressions or notches of the southern and eastern rims are of special interest. On the southern rim west of the Fitchburg & Worcester Railroad, are notches at elevations, from west to east, of about 1,130 feet (above Asnebumskit Pond), 820 feet (between Asnebumskit and Stone House Hills), 820 feet (between Stone House and Winter Hills), 750 feet (Chaffin Pond and the Boston, Barre & Gardner Railroad), 660 and 650 feet (at the head of Gates Brook, north of Summit Station). The Fitchburg & Worcester Railroad crosses the rim at an elevation of about 540 feet, and one mile farther east is a broad col, cutting the rim to 440 feet, in which head Muddy Brook on the north, and the valley of Lake Quinsigamond on the south. This is the only really important break in the southern rim. Passing to the eastern rim, the first notable depression is that occupied by the Central Massachu-

setts Railroad, two miles south of Clinton, with an elevation of about 360 feet. Two other passes in the immediate vicinity of Clinton, are nearly as low as this (370 to 375 feet). These are the broad pass occupied by the direct road from Clinton to Berlin, in the suburb of Clinton known as the Acre, and that occupied by the New York, New Haven & Hartford Railroad, at Bolton Station. The origin of these low passes, or wind-gaps, in the southern water-parting, or divide, of the Nashua Valley, as well as their glacial history, will be considered in later sections. It is a fact of exceptional importance in the glacial history of the Nashua Valley that no passes even approximately as low as those near Clinton occur in the next ten miles to the northward.

In Ayer the eastern ridge subsides completely and practically disappears, giving the Fitchburg and Stony Brook Railroads free admission to the valley. This broad breach — fully a mile wide on the 300 feet contour, omitting drumlins — of the eastern wall midway of its length and at the point where the valley is widest, is a fact of the first importance, the full significance and interest of which will be developed in a later section. North of this gap the eastern wall does not recover its normal height and continuity. The 400 feet contour encircles a goodly number of isolated hills (largely drumlins), while the 300 feet contour gives an almost continuous barrier as far north as East Pepperell. Further north a few points only reach that height, and the 200 feet contour barely serves to divide the waters of the Nashua and Salmon Brook.

Of the drift deposits of this region, the till, or bowlder clay, is, naturally, chiefly developed upon the higher land, where it is largely massed in the forms of drumlins and drumloid slopes: while the modified drift is confined to the low lands, assuming the form, chiefly, of delta plains corresponding in elevation in each part of the valley to the lowest pass or wind-gap to the southward, each lower depression in the southern and eastern rims of the valley having served in its turn, as they were uncovered during the recession of the ice-sheet, as an outlet of the glacial Lake Nashua, thus conditioning the successive levels of the lake and of its deposits. On the general map of the Nashua Valley (Pl. 1), the special accumulations of till are represented by appropriate conventions, and the modified drift is chiefly confined to the shaded areas. The detailed distribution and special features of the delta plains and their tributary eskers, and the quite

remarkable erosion slopes developed in them during post-glacial time by the Nashua River and its tributaries, will be fully considered in later sections.

The Buried Gorges of the Nashua Valley.

The facts developed by the borings on the site of the Wachusett Dam, as fully described in the first paper (pages 79–85), show that the Nashua here flows over a buried gorge 60 to 70 feet in depth between a precipitous and even overhanging wall of granite on the west, and a sloping wall of metamorphic slate or phyllite on the east. The contact of the granite and phyllite dips to the west 55° to 60°, and this fact has led to the under-cutting of the granite and tended to emphasize the unsymmetrical profile of the gorge. The interesting fact was also brought out by the borings that the bottom of this gorge slopes southward; and it is shown that the distribution of the material (sand, gravel and bowlders) filling the gorge confirms this indication that the gorge was excavated by a southward flowing stream, and hence not by the Nashua which now flows through the valley in the opposite direction, some 70 feet above the bed of the gorge. The head of this preglacial glen is at the Chestnut Street bridge, half a mile north of the site of the Wachusett Dam, where the granite bed rock comes to the surface, and from this head wall, or divide, as stated on page 85, a similar buried gorge probably trends northward.

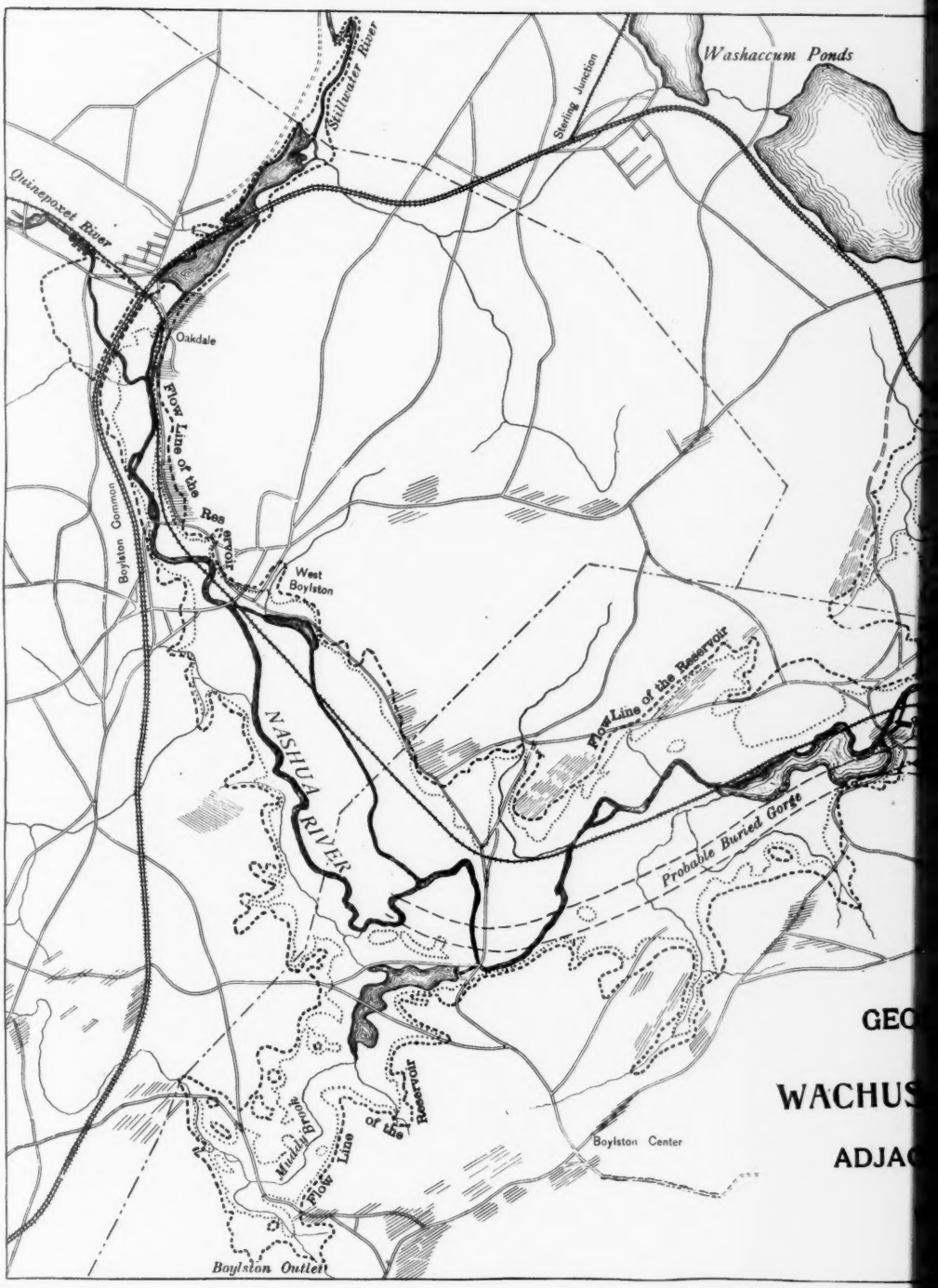
Although the indications afforded by the borings are so plain and unequivocal, they may be regarded as merely confirmatory of the main conclusion that the Nashua is here out of its preglacial course; for that is sufficiently obvious from the contracted and rocky character of this part of its valley as compared with the broad and smooth profiles of the valley to the north and south of Clinton.

On the west, the Wachusett Dam will abut against the precipitous eastern slope of the high ridge of granite, quartzite and phyllite, which is here known as Burdette Hill (530 feet), on which the Clinton reservoir is built. Further north, in Cedar Hill, this ridge bears the higher eastern part of the village of Clinton; and thus for a distance of nearly two miles it divides the Nashua Valley into a narrow eastern portion in which the river flows, and in which the main dam, known as the Wachusett Dam, is being built, and a broad western portion across which is rising the auxiliary dam nearly a mile and two-thirds

in length, known as the North Dike. The topography thus shows very plainly that the ancient channel of the Nashua lies to the westward, beyond Burdette Hill, and the question as to its precise location found a ready answer in the borings on the site of the North Dike.

The North Dike (Pl. 2) is divided, midway of its length, by the subordinate and composite ridge of metamorphic slate, or phyllite, west of Sandy and Coachlace Ponds, and 420 to 430 feet in maximum elevation, on the southern member of which the Catholic cemetery, now soon to be removed, is situated. The subdivision of the main valley by these ridges of granite and schist makes the vicinity of Clinton a highly advantageous site for the construction of the barrier required for the great reservoir. The eastern portion of the dike is to extend from the western slope of Burdette Hill across a level sand plain (Pl. 2), having a normal elevation above low tide of 380 feet, and the valley of Sandy and Coachlace Ponds to the cemetery ridge. West of the cemetery ridge the plain, preserving its normal elevation, is uninterrupted to the high hill at the western end of the dike.

This entire North Dike area, for a length east-west of over one and a half miles, and a breadth of 1,000 to nearly 3,000 feet, has been very thoroughly and systematically examined by wash drill borings, aggregating 1,131 in number, and nearly 18 miles in depth, the extreme depth being about 275 feet. A study of the data afforded by these borings has revealed the probable relief features of the bed-rock surface, as well as the great average thickness of the modified drift and the essential lack of correspondence between the present drift topography and the bed-rock contours, especially for the middle division of the valley between Burdette Hill and the cemetery ridge. Beneath the western division of the valley, beyond the cemetery ridge, the bed-rock surface is an approximate plain sloping southward more rapidly than the plain of modified drift which covers it at elevations above 300 feet, and slightly trenched by several southward-sloping valleys. Passing now to the middle division of the valley, we find that the western slope of Burdette Hill, which is but thinly covered by till, extends for fully 1,000 feet beneath the plain of modified drift with the normal height of 380 feet, to a well defined north-south depression with an average elevation of only about 200 feet, sloping both ways from a distinct water parting. A definite ridge of schist, which is covered at the highest point by 100 feet of modified drift,



GEO

WACHUS

ADJAC

GEOLOGICAL MAP

OF THE

WACHUSETT RESERV

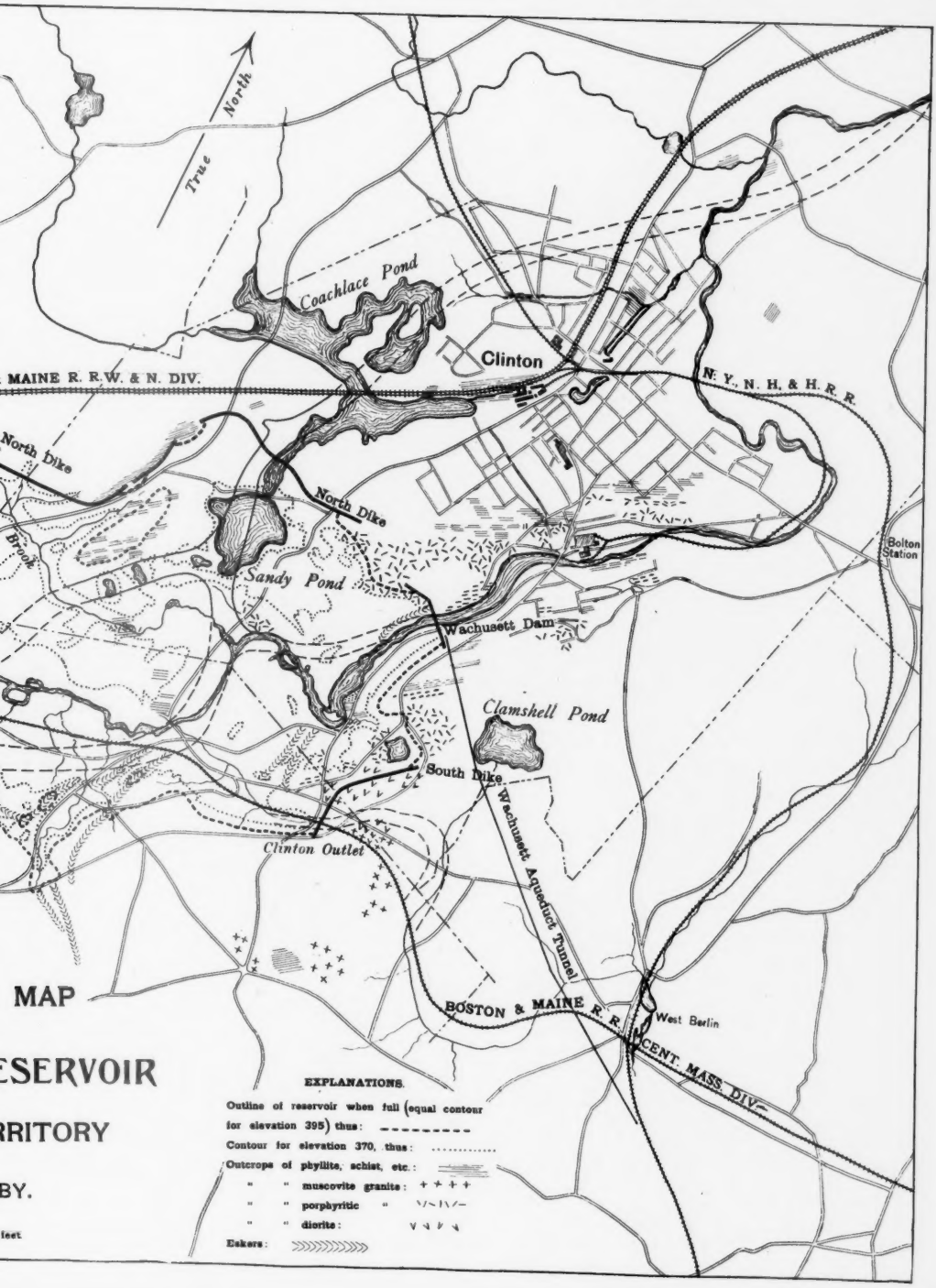
AND

ADJACENT TERRITOR

BY

W. O. CROSBY.

SCALE: 1 inch = 3200 feet.


True North
Coachlace Pond
Clinton
MAINE R. R. W. & N. DIV.
N. Y., N. H. & H. R. R.
North Dike
North Dike
Brook
Sandy Pond
Wachusett Dam
Bolton Station
Clamshell Pond
South Dike
Wachusett Aqueduct Tunnel
Clinton Outlet
BOSTON & MAINE R. R.
West Berlin
CENT. MASS. DIV.
MAP
ESERVOIR
RRITORY
BY.
feet
EXPLANATIONS.
Outline of reservoir when full (equal contour for elevation 395) thus:
Contour for elevation 370, thus:
Outcrops of phyllite, schist, etc.:
" " muscovite granite:
" " porphyritic "
" " diorite:
Eskers:

separates this depression from the deeper one beyond. Along the west side of the ridge, which is comparable with that on which the cemetery stands, but 150 feet lower, is an uneven bed-rock terrace several hundred feet wide, crossed by several spurs from the ridge, and with an approximate elevation of 190 to 210 feet. Over this terrace, with 120 to 130 feet of drift intervening, lies Coachlace Pond; and immediately beyond, and along a line parallel with the pond and the ridge, the bed-rock surface falls off abruptly about 100 feet more, and the drift reaches the astonishing thickness of 250 to nearly 300 feet.

The lowest elevation of the bed-rock surface determined by the borings is 96.5 feet on the center line of the main cut-off, nearly 200 feet west of Coachlace Pond. Since it is improbable that this boring, which has a depth of 272.5 feet, is located over the very lowest point in this profile of the valley, and especially since it failed to reach bed-rock, we may fairly assume that the minimum elevation of the bottom of the gorge on this line is at least as low as 95 feet, and probably as low as 90 feet. About 150 feet south and 50 feet east of this boring, the drill stopped at an elevation of 101 feet, without reaching bed-rock; but since this is south (up stream) from the first boring it may come quite as near the bed-rock as that. At points 100 to 200 feet west of these borings the drill reached elevations of 111 to 120 feet, and both north and south of this group of borings elevations between 110 and 140 feet were repeatedly reached; but in general, without reliable indications of bed-rock in what appears to be the axis of the gorge, some of the borings reported as reaching bed-rock probably ending either on bowlders or hard-packed gravel. That this depression is a veritable gorge is proved by the abruptness of its slopes at most points, the lateral gradients frequently exceeding 50 per cent. West of the gorge the bed-rock surface rises more abruptly and attains a greater elevation than on the east side. In the north part of the field it crosses the 300 feet contour within 300 to 500 feet of the axis of the gorge. It outcrops repeatedly and reaches an elevation of 424 feet in the cemetery ridge. This eastern member of the complex ridge bears northward and gradually dies out, terminating at an elevation of about 250 feet, some 500 feet north of the point where it passes beneath the surface of the plain. Between it and the similar member immediately west of the cemetery is a lateral rock valley or gorge, represented on the surface by a deep, large and

irregular kettle hole in the drift, and tributary to the main gorge some 600 feet north of Sandy Pond.

No borings have been made in Sandy Pond, which is a large kettle hole with a maximum depth below the water surface of about 66 feet (elevation 334 to 268); but a numerous series has been made, extending from the southwest end of Burdette Hill across the sand plain enclosing Sandy Pond on the east and south to a point about 2,000 feet southwest of the Pond. These borings have clearly located the continuation of the gorge, but have not determined its full depth. As marked on the map, it follows the line of small kettle ponds extending toward Boylston. A well defined branch or lateral gorge extends southeast from Sandy Pond, seeming to connect the main gorge with the present course of the Nashua at the mouth of Cunningham Brook and near the point where the river approaches nearest to the pond, (see the map of the Wachusett Reservoir, (Pl. 2). The granite of the Burdette Hill ridge outcrops just north of this gorge, between Sandy Pond and the river, while beyond the gorge the tapering extremity of this great granite dike reappears between the enclosing schists on Cunningham Brook over 2,000 feet from the river, and the less altered phyllite outcrops through a lobe of the sand plain, midway between the brook and the river on the southeast, and at the extreme southeast corner of the plain, opposite South Clinton Station. As the map shows, two courses for the buried gorge of the Nashua between Boylston and Sandy Pond may be considered. One is direct and conformable with the strike of the strata, while the other is roundabout, and crosses the granite dike, but accords best with the existing topography, following the present course of the Nashua to the mouth of the Cunningham Brook instead of abandoning it at Boylston. These rival courses are represented by dotted lines on the map, as an indication of their hypothetic character. I am, however, strongly disposed to accept the more southern and roundabout course; but the special conditions which seem to demand this choice may be most conveniently reserved for a later section. The reference of the river to the southern course would make of the deep gorge, demonstrated by the borings on the line of the kettle ponds southwest of Sandy Pond, simply the lower preglacial course of Cunningham Brook, which then joined the Nashua at the southern end of Sandy Pond.

At Boylston Village, soon to be a thing of the past, and the former site of Sawyer's Mills, the Nashua now flows over a prominent

ledge of phyllite, which also outcrops near the railroad on the north side of what was formerly the mill pond. These facts show that the river is here out of its preglacial channel, and a general survey of the situation indicates that the ancient channel or gorge lies to the south and not to the north of these obstructions, passing under the northern edge of a high sand plain, which was probably formed by glacial streams in an embayment of the ice-sheet. One important consideration pointing to this conclusion is found in the marked tendency which the Nashua everywhere exhibits to follow closely the southeast side of its valley. Again, the fact that between Cunningham and Muddy Brooks the course of the valley is distinctly oblique to the strike of the highly fissile phyllites gives the spurs projecting into the valley from the north decidedly retrograde, or up-stream, trends, as the map shows; and the ledges in the vicinity of Sawyer's Mills are probably an extension of the cemetery ridge, which is completely buried for more than a mile by the great delta plain of modified drift, and probably deeply notched where crossed by the preglacial channel of Cunningham Brook.

Between Sawyer's Mills and the mouth of Muddy Brook, the buried gorge probably continues along the southeast side of the valley. This is indicated by the ledges of schist in the middle of the valley northwest of Bee's Mills on the southwestward extension of another prominent retrograde spur. The valley turns here through nearly a right angle to a west-northwest course, and this circumstance must have tended to hold the preglacial Nashua against its right hand or southwestern bluff, although the fortuitous distribution of the modified drift has forced the modern stream to the opposite side of the valley. Between Muddy Brook and Oakdale the trend of the valley is approximately at right angles to the strike of the strata, which must tend to make the river more indifferent to the geological structure and the transverse bed-rock profiles of the valley more symmetrical. Hence we may assign the buried gorge a medial position, and the rapid narrowing of the valley in the vicinity of West Boylston makes it impossible that the river should depart widely from its preglacial course; although the ledge on which the dam is built shows that the entire indifference of the modern to the ancient channel still continues, with a strong probability that the latter is, as usual, to the southward, under the steep erosion slope of the high sand plain or terrace. At Oakdale the south branch of the Nashua is formed by the

confluence of the Stillwater and Quinepoxet Rivers, but the valleys of these streams are too narrow and too distinctly V-shaped to permit any wide separation of the ancient and modern channels. We need not doubt, however, that a bed-rock profile would show in every instance a U-shaped gorge at the bottom of the V-shaped valley.

The North Dike borings have definitely located the buried gorge of the Nashua River as far north as the Boston & Maine Railroad (Worcester, Nashua & Portland Division), where it crosses Coachlace Pond. Farther north no deep borings have been made, but that the rock gorge continues in the same general direction can not be doubted; and the outcrops, taken in connection with the general topography, suffice for an approximate determination of its course. Along the line of the railroad, northeast of the point where it crosses the pond, the phyllites outcrop, in part quite prominently, for half a mile, or nearly to the Clinton Station. These ledges are but the high points of a ridge which might be regarded as an extension of the cemetery ridge crossing the North Dike area, and dividing the basin of Coach lace Pond into two troughs. The eastern trough lies between this rocky ridge and the drumloid slopes of till on which the main part of Clinton stands. The axis of this depression, following Coachlace Brook, passes through the lower part of Clinton; and the chief difficulty in regarding this as the preglacial course of the Nashua is the consideration that since the till on the eastern slopes is probably, as the borings and cut-off excavations have proved it to be further south, of only very moderate thickness — 25 feet or less, and almost certainly less than 50 feet — the rock gorge would be improbably narrow, quite certainly not exceeding 300 feet on the 325 feet contour. The only difficulty with the alternative course, which passes under the railroad and the northern division of Coachlace Pond known as Mossy Pond, is that it breaks through the rock ridge supposed to connect the cemetery ridge with the ledges on the railroad instead of following the strike of the beds. But this difficulty vanishes if, as appears on the whole best, we regard the ledges on the railroad as the northern extension of the buried ridge disclosed by the borings on the east side of the deep gorge, this ridge declining or dying out southward, as the cemetery ridge does northward. Assuming, then, that the buried gorge, enclosed by these two ridges, underlies the basin of Mossy Pond, it probably follows further north the course indicated on the map, passing between the large and handsomely glaciated ledge of

metamorphic slate on North Main Street which was laid bare by the bursting of the Mossy Pond dam some twenty years ago, and the ledges among and over which the Nashua now flows in the vicinity of White's Mill in Lancaster. In other words, the ancient and modern channels probably cross near the mouth of Coachlace Brook, the former passing under the sand plain on the northern edge of which Lancaster Commons is situated.

In view of what precedes, we cannot escape the conclusion that the preglacial gorge of the South Nashua diverges from the present course of the river at or below Boylston, that the level of its bed in the vicinity of Coachlace Pond is nearly 200 feet lower than the present surface of the river south of Clinton, and fully 120 feet lower than the bottom of the buried gorge beneath the site of the Wachusett Dam; and it is probable that the latter gorge is the product of a minor preglacial tributary rising near the Lancaster Mills, and flowing south and west around the southern end of the granite ridge, with a total fall of at least 175 feet, to join the main gorge, the probable junction of the two gorges being near the present mouth of Cunningham Brook. In like manner, another minor stream flowed north and west from the Lancaster Mills, with still greater total fall, across the north end of the granite ridge, to join the Nashua near South Lancaster.

During the disappearance of the great ice-sheet from this region, the modified drift, for reasons which need not be specially considered at this point, was deposited in the latitude of Clinton to a greater height in the main valley than in the subordinate eastern valley, thus diverting the drainage and forcing the river through the eastern gorge over a water parting nearly or quite 175 feet high and giving rise to the abundant water power.

In Lancaster the Nashua River proper is formed by the union of its north and south branches, and from this point the river flows placidly through a broad, level, undivided and unobstructed valley, offering no clue to the precise course of the bed-rock gorge for more than eight miles to the line of the Fitchburg Railroad. One and a half miles west of Ayer Junction, where the railroad follows the north side of the river, the river falls over a ledge of slate, producing a small water power; and midway between this point and the junction is a prominent drumloid hill of porphyritic granite. Farther north, along the line of the river, outcrops, to be more particularly noticed later, occur at frequent intervals.

The absence of deep borings in the Nashua Valley north of Clinton deprives us of the definite data requisite to trace the buried gorge of the Nashua in all the lower reaches of its valley. Realizing, however, that a rock gorge whose bottom is less than 100 feet above the sea at Clinton must extend farther seaward than the mouth of the Nashua, I sought for evidence of its existence in the valley of the Merrimac.

Buried Gorge of the Merrimac River at Lowell.

Through the kindness of Mr. W. F. Sullivan, of the Lowell Water Works, I readily obtained data of the highest interest for that part of the Merrimac Valley. The elevation of the Merrimac is about 98 feet above low tide at the mouth of the Nashua, and 92 feet above the same datum above the dam at Lowell, where it falls 35 feet over a very rocky bed. Above the dam, on the north side of the river, between the Pawtucket Boulevard and the river, and at a height of about 5 feet above the river, the city has driven an extensive series of wells into the plain of modified drift. In the first group, about half a mile above the dam, the depths range from 13 to 53 feet. The principal group, embracing 169 wells of an average depth of about 40 feet, stretches along the river between $1\frac{1}{2}$ and 2 miles above the dam. The depths of the deepest of these are given as 73, 80 and 95 feet, the maximum depth occurring at the eastern end of the series. The bottom of this well is near sea-level, and all the deeper wells must be regarded as located in a preglacial buried channel of the Merrimac. The outcrops and shallow borings to bed-rock along the north side of the river from Pawtucketville to Centralville, although leaving something more to be desired, practically bar the way to a gorge large enough for the Merrimac, and 100 feet deep, especially when we consider that the great composite drumlin of Christian Hill, nearly 300 feet high, probably rests on a prominent bed-rock foundation, a continuation of the ledge forming Hunt's Falls, and not in a hole.

South of the river the ledges are planted so thickly, both north and south of the Pawtucket Canal, as to leave no loophole for the ancient river until we reach the valley of River Meadow Brook — a highly suggestive name in this connection — south of Ayer City. Here we find a broad and deep development of modified drift, crossed by the Middlesex Canal at an elevation of 12 feet above the Merrimac;

and both north and south of the canal are extensive plants of driven wells. The figures giving the depths of all the wells indicate, when plotted on the map, a deep rock valley crossing River Meadow Brook near the Framingham & Lowell Railroad. On Chelmsford Street, near Powell Street, bed-rock is 18 feet below the surface, and near the corner of Chelmsford and Forrest Streets what is supposed to be bed-rock, though probably a bowlder, was struck at a depth of 10 feet. But 1,000 feet to the northeast, near where Plain Street crosses River Meadow Brook, bed-rock was reached at 83 feet, or about 73 feet below the level of the Merrimac, and 19 feet above low tide. These data seem to locate the north side of the lost valley as passing beneath Ayer City. Farther south, at points on both sides of the railroad, borings 75 and 78 feet deep failed to reach bed-rock. That this depression is continued westward toward the Merrimac is indicated by an old well 53 feet deep, west of Chelmsford Street, in the gently sloping sandy valley of Black Brook. Following this course to the river, and keeping to the west of the rock outcrop at Middlesex Station, brings us opposite the deep wells on the north bank. The evidence is still incomplete, but it seems probable that a preglacial gorge of the Merrimac crosses the present course of the river at the point indicated, and passes south of Lowell through the valleys of Black Brook and River Meadow Brook. Beyond River Meadow Brook I have been able to obtain no significant data from borings or wells, but the surface features are not wholly devoid of interest in this connection. The ledges in River Meadow Brook near Gorham Street, and in the Concord River in the last mile of its course, during which it falls 40 feet, as well as the ledges at Hunt's Falls (9 feet) above Duck Islands, indicate plainly enough that the preglacial Merrimac did not follow that course. Eastward from the deep borings in the valley of River Meadow Brook is a level sand plain stretching to the Concord and beyond. Above the upper or Wamesit Falls on the Concord, the way appears clear for the buried valley until we reach the ledges on either side of the Boston & Lowell Railroad near the west bank of the river. This affords an apparent gap of 3,000 feet on the 100 feet contour. Farther eastward, toward Trull Brook, the available space is more restricted, being reduced nearly to 1,500 feet on the 140 feet contour between the ledges southeast of the Fort Hill drumlin. From this point the valley of Trull Brook affords, so far as can be judged from surface features, an easy and natural course for the buried gorge. It

is bordered by ledges and modified drift on the west, and by till on the east; and the gorge, if it exists here, is probably filled in this instance by till. This course by Trull Brook appears on the whole more satisfactory than the course from the head of Trull Brook northwest to the Merrimac below Hunt's Falls. Whatever course it may follow east of Fort Hill, it appears at least possible that the gorge of the preglacial Merrimac passes south of Lowell and under the Concord River, which was, according to this view, about a mile and a half shorter in preglacial times than now. The only alternative hypothesis worthy of consideration, viz., that the buried gorge of the Merrimac passes from 1 to 2 miles north of Lowell, from the vicinity of Tyng's Pond to either the gap between Christian and Loon Hills, or to some point near the mouth of Bartlett Brook in Methuen, is, possibly, more probable. It has the advantage of giving the Merrimac a more direct course to the sea. According to this view, the deep borings west of Lowell would represent the preglacial gorge of Stony Brook, now tributary to the Merrimac at North Chelmsford, and the deep borings south of Lowell might then be referred to the ancient channels of Concord River and River Meadow Brook. The present valley of the Merrimac below the Pawtucket Fall was occupied in preglacial times only by Beaver Brook.

The foregoing attempt to trace the ancient channel of the Merrimac around Lowell, is based upon the assumption that the Merrimac followed in preglacial times its present course from Lowell to the sea. Farther study has convinced me, however, that the preglacial Merrimac was tributary to Boston Harbor; and in this direction, southeastward from River Meadow Brook, we readily find a direct and unobstructed course for its buried gorge, as will be more fully pointed out in a later section.

We cannot, of course, suppose that these facts are unique, but they must be typical of the entire region. And it is interesting to reflect that the removal of the mantle of drift which now smothers and blots out the preglacial topography of southeastern New England, would reveal completely and deeply intrenched drainage systems — a peneplain traversed, in every direction and at frequent intervals, by deep, narrow, and intricate gorges, or, in other words, a youthful topography of far more rugged, picturesque, and difficult aspect than that which the ice-sheet has left us.

Pleistocene Changes in the Course of the Nashua River and the Composite Character of its Modern Channel.

The retrograde course of the lower Nashua with reference to the Merrimac, and of the principal tributaries of the Nashua with reference to the main stream, were referred to in the introduction as one of the special problems which a study of this river system presents. We come now to a more particular consideration of this feature. In a broader view of the problem we see not merely that the streams have retrograde courses, but that there is a very decided convergence of the drainage of the main part of the Nashua Valley toward the great break in the eastern rim of the valley at Ayer Junction. This break is so profound that the water parting between the Nashua River and Stony Brook becomes almost imperceptible, and appears to be composed wholly of drift. These facts naturally suggest an outlet for the drainage of the Nashua Valley in this direction; and this hypothesis is so attractive that I have tested it by a careful examination of the valley of Stony Brook from Ayer to the Merrimac at North Chelmsford. For the entire distance, from the Nashua south of Ayer Junction to North Chelmsford, we have a broad, open, and unobstructed valley, entirely out of proportion to the small stream which now occupies it. With one exception, within a few rods of the mouth of the brook at North Chelmsford, the valley is virtually devoid of rock outcrops, indicating a great average thickness of the drift. The valley is not only broad, but the breadth is remarkably uniform, so that it is practically a valley without a head, a mere strait some dozen miles in length between the Nashua and Merrimac valleys, and not at all the type of valley we should expect if it were due to the unaided activity of Stony Brook. Assuming an approximately uniform gradient for the buried gorge of the Nashua from Clinton (95 feet) to the Merrimac (sea level), via the valley of Stony Brook, the bed of the gorge should be 50 or 60 feet above sea level, in the vicinity of Ayer. Hence the depth of its burial probably diminishes from nearly 200 feet east of Ayer to about 100 feet at North Chelmsford. So far as can be judged from the surface indications, the gorge probably follows very closely the present course of Stony Brook, except at its junction with the Merrimac, where it probably turns slightly to the south to avoid the ledges of granite. The valley presents a continuous floor of modified drift, bordered on either side, except near its mouth, by till.

It appears, then, that the valley of Stony Brook offers no facts inconsistent with the view that it afforded, in preglacial times, an outlet for the drainage of the Nashua Valley; and that as a normal accident of the drift deposition, the valley was sufficiently obstructed, east of Ayer Junction, to turn the drainage northward across the low water-parting at East Pepperell. In corroboration of this view, we have not only the important fact that the drainage of almost the entire valley naturally converges upon Ayer, the probable preglacial confluence of the streams being shown by the broken lines on the map (Pl. 1), but the further fact that north of Ayer the present valley of the river becomes relatively narrow and more obstructed by ledges. The ledges west of Ayer Junction have been noted. About two miles northwest of the Junction are prominent slate ledges in the river, which probably represent a low place in an original water-parting between Mulpus Brook and the Squannacook River. At East Pepperell the indications are very plain that a continuous rocky ridge, having a general north-northwest and south-southeast course, separated the waters of the Nissitissit River from a small and rapid stream flowing northward to the Merrimac at Nashua. When the normal eastward drainage of the Nashua Valley was obstructed, this little stream, with a watershed equal to about six per cent. of that of the Nashua, suddenly fell heir to all the waters of its great rival, and Westford and Chelmsford lost the power, and consequent prosperity, which we now find at Nashua. If this be the true history of the Nashua, the main stream is distinctly composite, the flow has been reversed for the middle link, and it owes its distinction as a northward-flowing stream to an accident of its glacial history, the normal trend of the drainage being eastward from the common focussing point at Ayer.

In my opinion, a precisely similar case is presented by Salmon Brook, which so closely parallels the Nashua on the east. It rises in Groton within a mile of Stony Brook, and flows northward in a nearly direct line, fully 16 miles, to join the Merrimac at Nashua, hardly more than a mile from the mouth of the Nashua. It is clearly another triple composite, made up of a tributary of Stony Brook, a tributary of the Merrimac through Dunstable and Tyngsborough, and an original tributary of the Merrimac at Nashua.

The reopening of the Stony Brook outlet for the Nashua drainage, would make the courses of all the principal tributaries direct, with the exception of the North Nashua; but this important branch would

still appear hopelessly retrograde. Its course is essentially direct from its sources to North Leominster; but instead of turning southward here, running counter to the main stream, and reaching the common meeting-point after a journey of over 16 miles, it ought to continue eastward via Shirley Reservoir and village, reaching the goal in 7 or 8 miles. Between the North Nashua and Shirley Reservoir is a remarkable assemblage of drumlins, including both simple and highly composite forms. To trace a buried gorge across such an area, with any degree of certainty, is not a simple problem; but it happens, in this instance, that the most direct course is the one which would naturally be chosen on other grounds, since it offers the lowest barrier and is free of ledges. It passes first northeast and then east from North Leominster Station across a divide, some 70 feet in height above the river, and consisting, apparently, wholly of unmodified drift. A careful examination of this route discloses no more serious obstacle; and I believe that in preglacial times the North Nashua was, in its entire course from its source to the Merrimac, the most direct and most central member of the Nashua system, and in these respects best entitled to rank as the main stream.

South of North Leominster the present valley of the North Nashua is rock-bordered and narrow, and before reaching the mouth of Wekepeke Brook, it falls over two dams built on rocky ledges, apparently crossing a water-parting here. At the extreme north end of Ballard Hill, where the river turns from an east-west to a nearly due north-south course, is another dam on a bed-rock foundation. Below this dam the valley is again contracted, and a mile to the southward brings us to another dam, but with no ledge in sight. North and east of this great bend of the North Nashua is a high sand plain, but a marked north-northeasterly depression across it, along a line of ponds, suggests a preglacial outlet for Wekepeke Brook and its tributaries in this direction, as indicated on the map; while another small stream flowed south-southeast, from the last dam mentioned, to the South Nashua, in Lancaster.

On comparing these various instances of diverted drainage with reference to the nature of the obstruction, it becomes apparent that the modified drift has played a much more important part in this rôle than the till. The till, with the exception of the drumlins, was distributed with approximate uniformity on the melting of the ice; but rather more abundantly, as a rule, on the highlands than in the val-

leys; and since the drumlins were planted chiefly on moderately elevated rocky tracts, they have interfered but little with the courses of the streams. Assuming that the North Nashua once flowed eastward through the valley of Shirley Reservoir, then we have in North Leominster the most important instance in the entire Nashua region, of the obstructive agency of drumlins, and here the east-west course of the stream gave the ice an exceptional opportunity to scrape its gorge full of bowlder clay. The ice movement was most persistent and efficient in the north-south valleys, and tended to keep them clear of débris; when the ice became stagnant and slowly wasted by melting, it naturally lingered longest in these deep and narrow gorges. Hence, as the borings at Clinton so abundantly show, they are filled chiefly with modified drift deposited by the impounded waters.

Tertiary Changes in the Courses of the Nashua River and its Tributaries.

Important as were the changes in the drainage of this region during its glacial history, and due chiefly to the accidents of drift deposition, it appears probable that the changes of preglacial or Tertiary time, during the development of the coastal peneplain, were still more momentous. In fact, it may be doubted if many rivers have had in this respect a more remarkable history than the Nashua, or are now of a more highly composite character. The evidence of a considerable rearrangement of the drainage lines on the eastern slope of the Wachusett-Watatic ridge during Tertiary time, is found in some otherwise unexplained retrograde courses of the Nashua system, and especially in the deep notches or wind-gaps of the southeastern rim or water-parting of the Nashua Valley.

At the time of its elevation the Cretaceous peneplain was probably covered, at least as far inland as the Nashua Valley, by a mantle of Cretaceous sediments, and across this uplifted deposition plain the rivers probably found their way seaward in utter disregard of the structure of the hard rocks beneath, until, through the gradual disappearance of the still recent and essentially unlithified deposits they were superimposed upon the old erosion plain, or peneplain. This view, which is on *a priori* ground extremely probable, obviates the necessity of going back to pre-Cretaceous time for an explanation of the courses of the drainage at the beginning of the Tertiary cycle, and

affords an independent warrant for the assumption that the drainage, influenced only by the general uplift, was, in general, directly seaward and essentially non-sympathetic with reference to the structure of the peneplain. We thus find a ready explanation of the fact that existing or past drainage channels sometimes lie across the hardest rocks of the region, as where the preglacial main stem of the Nashua system, now the valley of Stony Brook, crosses the Westford area of granite for a dozen miles, from Ayer to the Merrimac, in close proximity to a belt of relatively yielding mica schist. It is not improbable, however, that on the Cretaceous peneplain, nearly a thousand feet above the present surface, the mica schist may have covered the granite.

We may safely assume that one main line of drainage at the beginning of the Tertiary cycle extended, as previously stated, from the sources of the North Nashua above Fitchburg in an easterly direction across the successive belts of gneiss, schist, argillite and granite to the Merrimac at North Chelmsford, the principal tributaries being the Nissitissit and Squannacook Rivers on the north, and on the south Wekepeke Brook, and a still smaller stream in what is now the main valley of the Nashua.

Two other, quite independent but long-since extinct main lines of drainage across the Cretaceous peneplain for the waters of what is now the Nashua Valley, are, I believe, indicated by the marked depressions or wind-gaps in the vicinity of Clinton and at the head of Muddy Brook in Boylston. These gaps are the more remarkable, and special explanations of their origin appear to be the more urgently demanded, since they do not represent exceptionally weak points in the geological structure; but, on the contrary, have been cut out of the most resistant rocks of the region, including the porphyritic and muscovite granites, diorite and quartzite.

The broad gap between Muddy Brook and the valley of Lake Quinsigamond, over half a mile wide, and, disregarding the drift, probably not much over 400 feet above the sea, with elevations of 700 feet on either side, is in the direct line of Stillwater River. The courses of the main tributaries of the Quinepoxet River — Trout Brook, South Wachusett Brook, etc. — suggest an independent outlet through the much higher (760 feet) gap occupied by Chaffin Pond. These two lines of drainage from the southern slope of Mt. Wachusett, converging south of Worcester, and tributary to Narragansett Bay, were later, but at an early period, merged in one nearer their sources by

the cutting through of the ridge southwest of Oakdale represented by Malden Hill, by the backward cutting of a tributary of Stillwater River. The points deserving special emphasis are: (1) that the Muddy Brook and Lake Quinsigamond pass is in the direct course of Stillwater River in its normal outflow from the Wachusett height of land, this drainage being distinctly retrograde with reference to the main line of the Nashua; and (2) that this broad and deep notch in the rim of the Nashua Valley, and the ample valleys leading up to it on either side, are entirely disproportionate to the insignificant rivulets which now pose as their architects. The utter inadequacy of these tiny brooks to the erosion of this great valley becomes still more obvious when we observe the slight fall on the south side, between the pass and Lake Quinsigamond, not exceeding the normal or average fall of the main line of the Nashua River. In short, this is a very clear and normal example of a beheaded valley, the Nashua River, by efficient backward cutting on relatively soft rocks, having captured at one stroke the entire Stillwater-Quinepoxet system.

Of the three low passes in the vicinity of Clinton, the most southerly, now occupied by the Central Massachusetts Railroad, and soon to be closed by the building of the South Dike, is the lowest, and, in this connection, the most important although they are closely united in origin, representing converging lines of drainage, branches of one ancient river. The elevations, as previously stated, range from 360 to 375 feet, or, disregarding the drift, from 340 (South Dike pass) to 375 feet, the elevations of the two northern and higher passes being approximately equal. The Muddy Brook-Quinsigamond pass marks the extreme southern angle of the Nashua Valley, where the drainage now turns through more than a right angle to the normal north-northeast course. On the other hand, the Clinton passes, which may be regarded in the general view as one, are, as previously noted, the deepest and only important notches in the eastern rim of the Nashua Valley south of Ayer; and, like the notch at Ayer, they represent a former focussing point of an independent but relatively unimportant west-to-east drainage system.

This system appears to have gathered water from the lower but not from the upper slope of the Wachusett ridge; unless we assume, as we may with a fair degree of probability, that the valley of the Washaccum Ponds and Cunningham Brook is an ancient alternative course of Stillwater River; or that the diversion of the Stillwater

from the Quinsigamond Valley was accomplished by this eastward-flowing stream and not by the comparatively modern Nashua. That one or the other, or both, of these views is true is most probable. The latter is specially favored by the fact that this eastward-flowing stream, which we will call Wachusett River, crosses the granitic ridge at a point three miles east of the Muddy Brook-Quinsigamond pass, where the ridge is from 100 to 200 feet lower, the actual difference in level of the two passes being nearly 100 feet. The rapid fall thus insured Wachusett River was sufficient to give even a small stream considerable erosive power and enable its southern tributary to cut back through the soft argillites until it tapped and diverted the Stillwater.

The pass at Bolton Station, northeast of Clinton, is in the direct line of the north branch of the Nashua River, below its great bend at the north end of Ballard Hill. The North Nashua, as we have seen, is probably a highly composite stream, the drainage of the upper section of its valley in preglacial times having been, as I suppose, directly eastward from Fitchburg to Ayer, as the main stem of the Nashua system, while the middle section, between North Leominster and Ballard Hill, was tributary northward through Wekepeke Brook to the main stem in Shirley, and only the lower section, in Lancaster, had a distinctly retrograde course. It was this relatively small stream, rising in the north part of Lancaster, and receiving a northeastern tributary in South Lancaster, that in early Tertiary times continued in its south-southeastern course, crossing the eastern ridge on the porphyritic granite at Bolton Station and flowing down the valley of North Brook to join, at West Berlin, the main branch of Wachusett River, which may have passed from the South Dike pass either north or south, but probably south, of Snake Hill. A third branch of Wachusett River probably had its source in Sterling and, converging upon Clinton, crossed the site of the village, formed the col between Cedar and Burdette Hills, crossed the eastern ridge by the middle pass, at the Acre, and thence by a natural and direct valley joined the main stream at West Berlin, which was thus the common meeting point for the Wachusett system. From West Berlin the broad valley of North Brook slopes gently southeastward across the Tertiary peneplain to join the valley of the Assabet in South Berlin; and the waters of Wachusett River, we may suppose, reached the sea, as do the waters of its shrunken trunk — North Brook, via the Assabet, Concord and

Merrimac Rivers; although an east-southeastern course to the valley of the Charles is, perhaps, more probable.

After the diversion of Stillwater River from the Quinsigamond Valley to form the main branch of Wachusett River, the drainage of what is now the Nashua watershed, with the exception of the extreme northeast corner, was accomplished by two eastward-flowing rivers — the Nashua and the Wachusett, the former crossing the granitic ridge now forming the eastern wall of the valley at Ayer, and the latter in the vicinity of Clinton. From their respective passes to the relatively low level of the Merrimac at North Chelmsford and Lowell was about a dozen miles for the Nashua and more than three times that distance for the Wachusett. The advantage of a more rapid fall enabled the Nashua to outstrip its southern rival in the work of cutting back its channel through the granite ridge and developing its system in the broad band of relatively weak argillites. The original divide between the two systems probably extended from Prospect Hill in Harvard, where the valley is still narrow, to the north end of Ballard Hill in Lancaster. The more aggressive Nashua gradually cut back this divide until it appropriated the water of the northern branch of Wachusett River, leaving the pass at Bolton Station dry. Later, the middle branch shared the same fate, and the pass at the Acre was abandoned. Each captive stream became at once, by virtue of its increased fall and power, an energetic captor; and thus the insignificant middle branch of the Wachusett, cutting back across the area of Coachlace and Sandy Ponds, absorbed first the water of Cunningham Brook; and then, with this reinforcement, it cut either southeastward across the granite ridge which was still covered by the phyllites, or southward toward Boylston, until it tapped and drew off the Stillwater branch or main stream of the Wachusett system, and the victory was complete. The narrow and more or less obstructed parts of the valley, as at Still River, Clinton, and Sawyer's Mills in Boylston, mark the positions of the divides which were pierced during this process of fluvial federation. The failure of the Nashua to make like acquisitions to the northward and thus preserve the original symmetry of its system, is due to a variety of causes, such as the greater hardness of the rock formations in that direction, the less rapid fall and the proximity on the east of the deep valley of the Merrimac.

After the close of this period of territorial expansion, the river continued to widen and deepen its valley, until in the late Tertiary

time the lower courses had been approximately graded for a breadth of from one to several miles. But at this stage the development of the Tertiary peneplain was arrested by the strong elevation of the land in early Pleistocene time which ushered in the great ice age. This rejuvenation of the streams (in volume, possibly, as well as in gradient or slope) naturally led to a rapid deepening of their channels and the development of the system of deep U-shaped gorges revealed by the borings. When the ice-sheet disappeared, these gorges were left full to the brim of drift, chiefly modified; and as the result of late glacial and post-glacial oscillations of the land, the Tertiary peneplain now stands, in this part of New England, from 100 to 200 feet above the sea.

Taking a broader view of the drainage of Eastern Massachusetts, attention is attracted to the course of the Merrimac below its great bend at North Chelmsford. When the Cretaceous peneplain was recently uplifted, and the streams were finding their way seaward across its sedimentary cover — the young coastal or deposition plain — it is probable that the Merrimac, uninfluenced by the structure of the hard rocks beneath, continued in its normal southeastward course until it became tributary to Boston Harbor, following the line of the Boston & Lowell Railroad and Middlesex Canal to the valley of Mystic River. This route, which now barely rises above the 100 feet contour, lies, between the Merrimac above Lowell and Woburn, across a nearly level plain of modified drift several miles wide, remarkably free from rock outcrops, and bordered on the northeast and southwest by land from 50 to 200 feet higher. In other words, it may be regarded as a wide and probably a deep valley filled to the brim with glacial sand and gravel, and merging imperceptibly with the valley of the Mystic, which has no proper head, and is in size quite out of proportion to the diminutive stream, miscalled a river, which courses sluggishly through it. This broad and direct valley is in striking contrast with the narrow, crooked, and much longer valley of the modern Merrimac between Lowell and the sea.

It might be supposed that the Merrimac was diverted from its southeastern course during Tertiary time by the backward cutting on a band of relatively weak rocks (the Merrimac slates) of a small stream following the present course of the Merrimac below Lowell. But it is quite as probable that the Merrimac held to the more direct and shorter southeastern course until the advent of the ice-sheet, which

left sufficient drift in its valley to turn it over a low divide at Lowell into the valley of this northeastward flowing stream. This view explains why the deep buried gorge of the Merrimac can not be satisfactorily traced around the southeast side of Lowell, from River Meadow Brook to Trull Brook. From River Meadow Brook it probably follows approximately the line of the Middlesex Canal to Boston Harbor. As I have elsewhere pointed out, the Merrimac probably continued to hold to this line during the recession of the ice-sheet, while the ice still occupied what is now the valley of the Merrimac northeast of Lowell, the shallow glacial lake thus resulting accounting for the broad development of modified drift southeast of Lowell.

The Concord River, according to this view, probably joined the Merrimac in preglacial times in North Billerica; and the southeastern course here assigned the Merrimac increases the probability that the course of the ancient Wachusett River was also southeasterly from West Berlin to the valley of the Charles and Boston Harbor, appropriating on the way the headwaters of what are now the Assabet and Sudbury Rivers.

In closing this section we may note the interesting fact that the general result of the rearrangements of the drainage discussed in this paper, whether due to the fluvial competition of Tertiary time, or the accidents of drift deposition, has been to bring the streams more and more into harmony with the geological structure, so that, in spite of the drift, the adjustment is well nigh complete, at least for the main lines.

Lake Nashua.

The Quinepoxet and Boylston Stages.

The history of Lake Nashua commenced when the retreating margin of the great ice-sheet first began to uncover the southern water-parting of the Nashua Valley. The southern end of the valley is divided by the north-south ridge terminating in Malden Hill, south of Oakdale. The minimum elevation of this ridge, just south of Malden Hill, is about 770 feet. West of the ridge, on either side of Stone House Hill, are two passes across the water-parting at about the same height — 820 to 830 feet. But the only pass that need be specially noted is that occupied by Chaffin Pond and the Boston, Barre & Gardner Railroad, with a height of 760 feet. As long as the ice

retained its hold on Malden Hill this pass, discharging southward into North Pond and Blackstone River, must have afforded the principal outlet for the impounded waters of the Quinepoxet Valley; and it is proposed to designate this the Quinepoxet stage of Lake Nashua, with a normal level of about 760 feet. It affords a ready explanation of the most of the modified drift observed in the Quinepoxet Valley above Oakdale.

East of the Malden Hill ridge we find passes at heights of 660 and 560 feet, the latter being occupied by the Fitchburg & Worcester Railroad. But these must have been short-lived as water courses, because immediately to the eastward, as previously noted, is the broad pass between Muddy Brook and Lake Quinsigamond, only 460 feet or less in height. The portion of the lake tributary to this most important of the southern outlets, the ancient and heheaded channel of Stillwater River, lies chiefly in the towns of Boylston and West Boylston, and may be appropriately known as the Boylston stage. When the ice filled this valley, but had disappeared from the bordering ridges, embayments in the body of the ice, connected by marginal streams must have been a characteristic feature, giving rise to marginal deposits of modified drift, and explaining the fact that the deposits of this stage rise to somewhat greater heights than the outlet. The same agency, coöperating apparently with a powerful subglacial stream, spread extensive deposits of modified drift in the Quinsigamond Valley sloping southward from this outlet; and in the outlet itself, nearly a mile in extreme width, the undulating and kame-like character of the deposits of sand and gravel testify to strong and variable currents. The opening of the Boylston outlet involved a change of level of about 300 feet, and consequently, such a complete abandonment of the Quinepoxet area that the two parts or stages of the lake nowhere overlap, but appear on the map as entirely distinct and separate bodies of water. It is probable, however, that they were in part contemporaneous lakes at different levels, Quinepoxet Lake continuing until the ice relaxed its hold on Malden Hill.

It is probable that toward the end of the flow through the Boylston outlet, when the water was beginning to find an outlet elsewhere, this outlet became somewhat clogged up and thus raised above its normal height, and the seasonal variations in the volume of water must have caused changes of level, so that it is not surprising that the delta as well as the marginal deposits of this stage vary somewhat in height.

The Boylston stage clearly occupied the valleys of Stillwater River and the Washaccum Ponds, agreeing with the Quinepoxet stage in having its major diameter transverse to the axis of the valley. This is, also, but one of many indications that the ice front held in general a northwest and southeast direction. The contour lines on the Worcester and Marlboro sheets of the topographic map show with approximate accuracy what is left of the special delta and terrace plains of modified drift, ranging in elevation from 440 to 460 feet, formed during this stage. Naturally enough these short lived lakes did not build normal deltas over their entire areas; but we must, in this connection, make liberal allowance for the postglacial erosive action of the river. Commencing on the west, we find a small but normal development of this plain rising abruptly above the village of Oakdale. South of Quinepoxet River it is continued along the south side of the valley as a broad level terrace, with an abrupt erosion slope facing the river to Boylston Common, where it is very perfectly developed, and is marked by several kettles. The plain broadens here to half a mile, but is less perfect in surface, appearing to consist of a thin deposit of modified drift over till. South of the high quartzite hill rising boldly from the inner margin of the valley west of Muddy Brook, the modified drift has a strong development, with undulating contours, and several large and deep kettles along the eastern margin of the plain. The complex of eskers and kames in the Muddy Brook-Quinsigamond outlet has been noted. Along the line of the Fitchburg & Worcester Railroad the modified drift rises, as previously noted, about 100 feet above the normal level of the Boylston stage, and has an important development in the pass 560 feet in height occupied by the railroad, sloping gently southward from the pass in a broad apron plain. This is clearly a record of the time when the ice still filled the Muddy Brook-Quinsigamond outlet, and an important marginal stream, embracing, possibly, the whole of the Quinepoxet and Stillwater drainage, escaped from the valley at this higher level. Incidentally, we have here, also, evidence of the general northwest-southeast trend of the margin of the waning ice-sheet. Along the east side of the Muddy Brook Valley the Boylston plain is distinctly developed, and is especially perfect toward the north, where it rises in a very steep erosion slope from the river and Dover Pond; and again, southeast of Sawyer's Mills, an unmistakable erosion scarp rises from the mill pond (now drained) to a plane of the normal height

fully half a mile square, and extending southward half way to Boylston Center and eastward nearly to the South Dike pass. East of the mill pond the erosion scarp is transferred to the Clinton (370 feet) plain; and the Boylston plain, rising 70 feet above the Clinton plain, presents to the northward a normal ice margin, with a series of eskers which, apparently, mark the courses of streams tributary to these high deltas. Immediately east of South Clinton Station, the Clinton plain is crossed by two eskers from 400 to 500 feet apart and trending in a south-southwest direction. The western esker, which here barely reaches the level of the Wachusett Reservoir (395 feet), bears to the southwest, and, crossing the road to Boylston Center about one-fourth of a mile from the station, is represented by the two north-south islands in the reservoir on the west side of the road (437 and 422 feet). As it approaches the irregular northern or ice margin of the Boylston plain, the esker turns quite abruptly to a general westerly course, and forming one large island in the reservoir, continues as a more or less discontinuous, serpentine ridge, parallel with the high slope, to Sawyer's Mills, where it turns to the southwest as if seeking the Boylston outlet at the head of Muddy Brook. The course of this glacial stream is marked also by a series of deep kettles. The eastern esker near South Clinton Station forms a small island (400 feet) in the reservoir and continues in a general southerly direction up the east side of the valley of a small brook (a bay of the reservoir) with a slight interruption, across the new road to Boylston Center, toward the low place (480 feet) in the water-parting about a mile south-southwest from the South Dike outlet. As we approach this outlet, the modified drift which can be referred to the Boylston stage of Lake Nashua becomes more and more uneven, patchy, and esker-like, but does not wholly cease until the outlet is reached.

That these high level deposits of modified drift were, in the main, formed in standing water, and only to a limited extent by marginal streams, is indicated by the considerable breadth of the plains at some points, and also by the more or less distinct depression which usually, especially east of Muddy Brook, separates the sand plains from the slopes of ledge and till rising above them on the southeast. This depression or channel is the normal product of the water flowing over the surface of the delta, where the growing edge of the latter approaches the limit of the basin. The water must then maintain a passage to the right or left, parallel with the front of the delta.

It is an interesting and significant fact that the eskers referable to each stage of the glacial lake trend, in general, toward the nearest outlet of that stage, and that they are, as a rule, confined to the side of the valley (southeast and south) in which the outlets occur. Their absence from the middle of the valley would, however, be satisfactorily explained by the subsequent erosive action of the river. Very obviously, the subglacial drainage, moving in general up hill, with reference to the contours of the valley, in obedience to the hydrostatic pressure due to the great thickness of the ice-sheet to the northward, became more and more concentrated toward the outlets. A certain regard for the topography is thus indicated; but the unmistakable fact that the esker-building streams of the Boylston stage virtually flowed right by the South Dike outlet of the Clinton stage to seek much higher and more distant outlets then uncovered, shows that proximity to the margin of the ice was a still more potent factor than the topography in controlling and directing the subglacial drainage. It may be noted in passing, also, that we have in this indifference of the Boylston drainage to the Clinton outlet very convincing proof that the general trend of the ice margin at this time was northwest-southeast; for unless the ice had rested heavily upon the country to the east and southeast, it is inconceivable that the water could have resisted the natural tendency to escape by the South Dike outlet.

The only distinct or important occurrence of modified drift on the north side of the valley which can be referred to the Boylston stage of Lake Nashua is that in the vicinity of West Boylston Village and between West Boylston and Oakdale. It is very much subdivided and isolated by subsequent erosion; but we have one remarkable perfect remnant in the beautiful plateau rising abruptly on the east side of the village. This eroded plain, 440 to 460 feet in height, was probably once continuous with that at Oakdale and Boylston Common, filling the entire valley to this level, as far down, possibly, as Sawyer's Mills. The erosive action of the river and its tributaries upon this plain has been very great, so that only discontinuous marginal remnants or terraces now remain; and the fact that these are now more extensive and continuous on the south than on the north side of the valley is an indication that it suffered from the erosive action of glacial streams during the subsequent Clinton stage of Lake Nashua. The eskers in the valley of Stillwater River probably mark the shifting course of a subglacial stream tributary to the earliest stage of this plain.

It may be noted in passing that the draining of the Quinepoxet stage of Lake Nashua exposed its sediments to rapid erosion, thus supplying a part, possibly a large part, of the material for the upper (western) section of the Boylston plain, and making more probable the former continuity of this plain above Muddy Brook.

Northward from West Boylston the modified drift is continuous, across a low divide northwest of French Hill, with the very perfect plain in the south part of Sterling which embraces the Washaccum Ponds. The normal elevation of this plain is about 460 feet; and it is separated by a low divide from the gently sloping plain of about the same elevation, extending up the valley of Stillwater River toward West Sterling. A low ridge of rock and till across the east end of the Washaccum Valley, reinforced, probably, by the retreating margin of the ice-sheet, prevented the water which formed the Washaccum plain from finding an outlet to the eastward. This water probably communicated with the main body of Lake Boylston at Oakdale, through the pass occupied by the railroad and a branch of Stillwater River, and the modified drift crossing the low divide southward to West Boylston Village may, perhaps, be attributed to an earlier, subglacial, flow of water. The Washaccum plain rises gradually northward along the line of the railroad to the narrow and sharply-defined pass at Sterling Center, between this valley and the valley of Wekepeke Brook; and this sloping head of the plain was clearly formed chiefly by an overflow stream from an independent glacial lake in the Wekepeke Valley; but an earlier, subglacial flow along this line is indicated by a still traceable line of eskers. East Washaccum Pond clearly represents a part of this basin which was not covered by the delta, another indication that the main flow of water was not to the eastward, while West Washaccum Pond and Muddy Pond may, apparently, be regarded as true kettle ponds.

The high slopes of rock and till bordering the basin of Lake Boylston on the north make it unnecessary to postulate an ice barrier for the maximum stage of the lake, or to suppose that the delta plains were built against a wall of ice, except east of Sawyer's Mills, where, as previously noted, an ice margin is clearly indicated. I conclude, therefore, that at the close of this stage of Lake Nashua the more or less lobate front of the ice extended, as shown on the maps, from the South Dike pass westward across the main valley to the high ground about the head of Cunningham Brook, and thence northward across

the group of drumlins between Coachlace Pond and the Washaccum Ponds.

During the lowering of the water by the uncovering of the South Dike pass, a marginal stream flowing along the front of the ice-sheet, or possibly a glacial or subglacial stream, formed the small plain immediately north of Sawyer's Mills, which rises somewhat abruptly above the Clinton plain on the north (Pl. 3), to elevations of 395 to 405 feet, being distinctly intermediate between the Boylston and Clinton levels. Southward, toward the river, this little plain, which was virtually formed in an embayment between the ice on the north and the land on the west, is cut off by the steep modern erosion scarp, and we cannot observe its relations in this direction to the other plains. It is very improbable, however, that it ever extended far beyond its present limits. Westward, as we should naturally expect, the modified drift referable to this plain gains in height and approximates to the Boylston level.

The Clinton, Wekepeke and Ayer Stages.

When the ice margin had retreated along the eastern water parting to the pass now occupied by the Central Massachusetts Railroad, and to be later closed by the South Dike, the level of the lake was lowered nearly 100 feet to the Clinton stage; and its waters probably became tributary, the Concord and Merrimac Valleys being still occupied by ice, to Boston Harbor instead of Narragansett Bay. This is an ideal outlet — narrow, well defined, and with every indication of a strong stream flowing swiftly down around Snake Hill into the valley of North Brook (Pl. 4). In the lower part of its course, especially, this stream washed away all the finer part of the till, and its path is now strewn with thousands of residuary bowlders. That this is the work of a long-continued torrent, and not of some transitory cloud-burst, is proved by the pot-holes to be seen in the bed of North Brook at West Berlin, in situations which make it well-nigh impossible that they can have been formed by the modern brook.

The minimum elevation of the water-parting in the South Dike pass is 365 feet, or nearly 370 feet before the construction of the railroad. The elevation of the bed-rock surface at the same point is 358 feet; but to the east and southeast, as shown by the numerous borings, the bed-rock surface falls off for some 200 feet to elevations of about 340 feet (minimum 339.3), and then rises gradually again,

PLATE 3.

View looking southwest across the Clinton Plain at a marginal plain of the Boylston Stage of Lake Nashua. Both plains are cut off on the left by the erosion-bluff of the Nashua River in the vicinity of Sawyer's Mills.

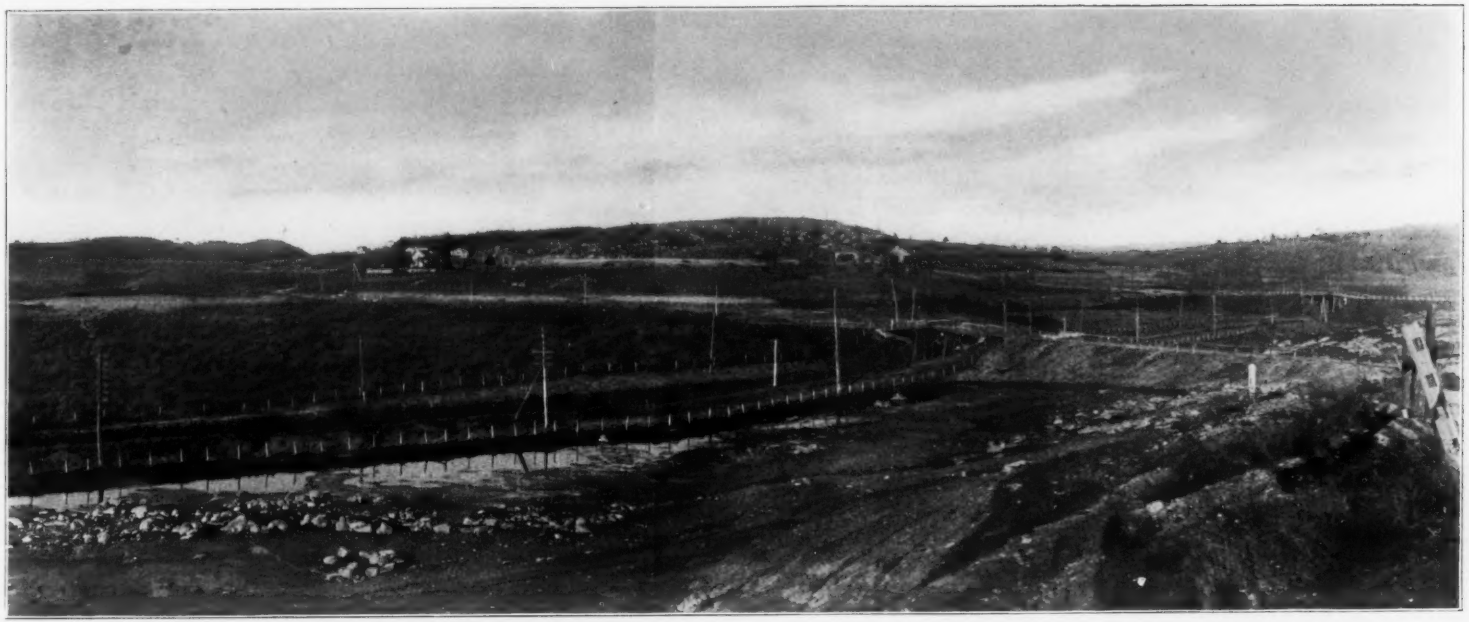


PLATE 4.

View looking north across the South Dike Pass, or the outlet of the Clinton Stage of Lake Nashua. It shows a small portion of the Clinton Plain, and, in the distance, Burdette Hill on the left, Carvill Hill in the center, and Larkin Hill on the right. The course of the Outlet Stream was from left to right, along the line of the railroad.

reaching in 150 feet farther elevation 354. There is no evidence of a distinct bed-rock gorge here, but rather of a wide col or saddle with gentle slopes in all directions.

Plate 4 is a comprehensive view across this outlet, looking northward from a distinctly drumloid slope of till on the northwest side of Mile Hill (— feet, muscovite granite), with Burdette Hill (530 feet, porphyritic granite) in the distance on the left, Carvill Hill (535 feet, a broad dome of porphyritic granite) in the center, and Larkin Hill (560 feet, diorite and quartzose schist) on the extreme right. To the right of Larkin Hill, and well beyond the limits of this view is Snake Hill (— feet, muscovite granite). Between Burdette Hill and Carvill Hill, excavated in a band of soft phyllites, is the gorge of the Nashua River. Between Carvill Hill and Larkin Hill is Clam Shell Pond. The north side of the outlet is immediately formed by an undulating ridge of diorite, which, with elevations of from 390 to 410 feet, and thinly covered at most points by modified drift, extends northeastward for nearly half a mile to the base of Carvill Hill.[1] Of the two roads crossing the railroad in the foreground, the nearer one is the old road, shown on the map, and the farther one is the new road, built to take the place of this. The South Dike will start from the slope of till between the two roads, and cross the outlet nearly parallel with the old road (See map) to the low ridge of diorite, and then turn to the northeast along the top of the ridge.

The axis of the bed-rock depression in this pass does not follow the line of the railroad, but, crossing the railroad near the new highway, it bears to the southwest, passing obliquely under the slope of bowlder clay in the foreground of Plate 4, following the granite diorite contact regardless of the drift contours. As the plate clearly shows, the till, from a part of which the surface soil has been removed, extends north to the railroad; while the brushy slope north of the railroad is modified drift — the edge of a small development of the

[1] When discussing, in the paper on the geology of the dam and tunnel (Vol. XII., p. 76), the relations of the diorite to the muscovite granite I omitted to cite the evidence of the South Dike borings. The diamond drill borings are especially important in this connection. The cores show normal development of both the diorite and granite; that the contact is near the railroad and the axis of the depression; that the granite slopes down to the northward under the diorite; that there are dikes and dikelets of granite in the diorite; that, while the diorite retains its normal texture up to the contact, the granite becomes near the contact fine-grained and finely laminated or gneissoid (flow-structure); that the two rocks are firmly welded together; and, finally, that it is in every respect a typical contact, not due to faulting, and resembling that between the diorite and the porphyritic granite.

Clinton plain (380–385 feet). These facts make it clear that the pass is, and must have been during the existence of Lake Nashua, filled to a depth of twenty-five or thirty feet with bowlder clay; and hence we cannot suppose that the outlet stream flowed upon the bed-rock surface at its lowest point, nor necessarily at any point. In fact, it seems most probable that the stream flowed across the till regardless of the bed-rock contours, and that erosion soon developed a pavement of residuary bowlders, of which there are indications in the photograph, which greatly retarded the deepening of the channel. Another factor, which operated to the same end, is the slight fall of the outlet valley for the first half mile, insuring a placid current of slight erosive power. The broad channel of this stream is now a meadow which crosses and recrosses the road to West Berlin, and describes a full semicircle before returning to the railroad southwest of Snake Hill. In rounding Snake Hill the valley steepens, and a rush of water is indicated by the profusion of residuary bowlders previously noted.

With the opening of the South Dike pass came a rapid development of the Clinton plain, made possible by the necessarily rapid erosion of the high and deep deposits of the Boylston stage. In fact, the waste of the Boylston plain along the axis of the valley in the first few years after it became exposed to the rush of the Nashua and its tributaries with a fall of from 10 to 20 feet per mile must have been enormous; and we cannot escape the conclusion that through the coöperation of the Nashua with the glacial streams from the northward the Clinton plain was developed continuously along the southern margin of the ice to the outlet, the level of which was probably raised somewhat by the extension through it of the coarse topset layers of the delta.

The continued recession of the ice margin uncovered in succession the two passes of slightly greater but approximately equal elevation at the Acre, above the Lancaster Mills, and at Bolton Station. Judged by the rock contours, these passes are much higher than the South Dike pass, for the bed-rock (porphyritic granite) comes to the surface in both of them; and they were, therefore, less subject to changes of level through the washing away of the drift by ex-current streams. It is quite possible, however, that during the vicissitudes of erosion, deposition, ice dams, etc., all three of the Clinton passes were brought into play as outlets for the waters of the Clinton stage; although the South Dike pass, through its more southern location and consequent

earlier discovery, and greater depth, especially as measured on the bed-rock, must be regarded as the main outlet. The slight amount of modified drift in the valley immediately southeast of the Acre is not suggestive of any important outflow of water at this point; but we must recognize that an ex-current stream flowing over a granite dam could not be well charged with detritus. Extending northeastward from the Acre along the steep slope above the Nashua River, and on the general level of this pass, is a more or less distinct terrace of modified drift which is conceivably but not probably a marginal remnant of a once continuous plain extending westward across the basin. More probably, it is a free beach deposit; or perhaps, and with still greater probability, it marks the channel at an earlier period, when the valley was still filled with ice, of a marginal stream due to the interception of the drainage from the ice by the ridge of granite. The latter explanation is certainly demanded at Bolton Station, where this bench of modified drift widens into an undulating plain through which the railroad makes a deep cut. The former extension of this plain across the wide and deep valley is highly improbable; its breadth and volume, and its position in the lee of the large hill northeast of Clinton, forbid regarding it as a beach deposit; and the only alternative, apparently, is to consider that it antedates the complete evacuation of this part of the valley by the ice and was formed by glacial streams in a marginal embayment of the ice. Farther north, at the same general level, on the side of the valley above Still River and Lancaster Commons, are eskers trending in the direction of this embayment and the pass at Bolton Station. The glaciated and *roche moutouee* outlines of the porphyritic granite in this pass would seem to indicate that the outflow of water at this point, whether from Lake Nashua or an anterior marginal lakelet, was not very prolonged. But, on the other hand, we find sloping away from this pass to the east and southeast, into the valley of North Brook, a beautiful and almost ideal apron plain, a nearly perfect alluvial cone, which testifies unequivocally to an outflowing stream well charged with detritus, and hence quite certainly a marginal stream. That it was a short-lived stream and came to an abrupt end, probably when the continued waning of the ice allowed it to reach the South Dike pass, is indicated by the absence of fluvial erosion on the granite and the absence of erosion channels in the apron plain, such as must have been developed during a gradual slackening of the flow.

Pauses in the recession of the ice margin are rather seldom indicated by distinct morainal accumulations in this region, showing, apparently, that on this rugged surface, with strong gradients to overcome, the ice had already become essentially stagnant. But we have, perhaps, a slight exception, dating from the Clinton stage, in the basin of Clam Shell Pond, which is enclosed by and appears to be due wholly to two short but very typical moraines crossing the valley between Carvill Hill and Larkin Hill. The northern moraine is a particularly fine and strong example, with a great profusion of large bowlders. The southern moraine is more irregular and its low eastern end determines the water level of the pond (400 feet). The elevation of the bottom of the pond is 370 feet, or about the same as the Clinton outlets of Lake Nashua.

The delta plains of the Clinton stage, with normal elevations of 375 to 385 feet, are most broadly and typically developed in the districts immediately northwest and southwest of the village of Clinton, or in that part of the valley between South Lancaster and Boylston (Sawyer's Mills). They are, in part, indicated with a good degree of accuracy by the contour lines of the topographic map; and those southwest of Clinton are still more clearly and accurately expressed by the contour line of 370 feet on the map of the Wachusett Reservoir (Pl. 2), this contour tracing the outlines of the plains very closely where they are developed to the normal elevation. Although, as previously noted, the Clinton plains must, in consequence of the generous supply of material afforded by the fluvial erosion of the Boylston plain, have been developed continuously or nearly so over all the upper part of the valley, the postglacial erosive action of the river has left, as a rule, only meager remnants of it above Boylston; and above West Boylston it merges with or is lost in the modern flood plain of the river. North of Boylston the valley is much broader, and the ravages of the river relatively much less, so that over an area of several square miles the deltas of the Clinton stage are preserved almost intact. In fact, it may be doubted if anywhere in this region can be found more normal or striking examples of this phase of the modified drift. The deforesting of the area to be covered by the reservoir brings out the various features of the plains, ice margins, normal delta fronts, eskers, kettles, erosion slopes, etc., in all their pristine distinctness and perfection, so that even in a merely topographic sense a very unusual opportunity is temporarily presented to the student of

glacial geology. But in addition to this, the numerous deep borings in the vicinity of the North Dike, and the subsequent deep cut-off excavation in the construction of the dike itself, have thrown a flood of light upon the structure and composition of these plains. These considerations, collectively, demand such a thorough and detailed study as would carry us beyond the reasonable limits of this paper; and the further special consideration of the Clinton plains, which are unquestionably equal in interest to all the rest of the modified drift of the Nashua Valley, is, therefore, reserved for a second paper.

North of Clinton the ice margin appears to have retreated too rapidly to permit the formation of extensive plains of normal height in water from 100 to 250 feet deep, and the broad level plain, forming the bottom of the valley 260 to 280 feet in height may be referred to the next lower (Ayer) stage, which began when the recession of the ice uncovered the broad and deep pass connecting the modern valleys of the Nashua and Stony Brook. To this stage may be referred the plain in South Lancaster on the northern lobe of which Lancaster Commons stands. This is a remnant of the delta formed in the head of the lake from the waste of the Clinton plains. But the chief deltas corresponding to the level of the Ayer outlet are the broad plains south and west of Ayer Junction.

The valley of Wekepeke Brook lying west of the Ballard Hill ridge had for a time an independent lacustrine history. When the ice covered the notch in this ridge occupied by the Boston, Clinton & Fitchburg Railroad, the water stood at an elevation of about 500 feet and discharged southward through Sterling Center, along the line of the Fitchburg & Worcester Railroad, into the Washaccum area of the Boylston stage, making an important contribution in the form of an apron plain to the 460 feet plain enclosing the Washaccum Ponds. Later the water found the eastern notch referred to, and, its level falling to about 420, it became tributary to the Clinton stage. That this condition did not long continue is indicated by the absence of any important plain development of corresponding height in the Wekepeke Valley.

The exceptional heights reached by the modified drift along the east side of the valley in Lancaster, and about Ban Hill Pond in Harvard, are probably best explained by deposition in marginal lakelets, while the ice still filled the valley.

My detailed study of the modified drift has not extended over the

Groton and Fitchburg quadrangles of the topographic map, and I am not fully prepared to explain the extensive plain or mass of modified drift having a normal height of 400 to 420 feet, lying between the Fitchburg Railroad on the north and the North Nashua River on the south. I can only suggest that, perhaps during the Wekepeke stage, and while the ice in the main valley was still joined to the Ballard Hill ridge, a great embayment was formed whose level was determined by the outlet in the upper Wekepeke Valley. A rational explanation of such an embayment may be found in the principle formulated by Chamberlin that in the case of ice moving on an elevated broken surface the loss by ablation is not promptly made good by an influx from the north, and a depression results. A complete land barrier is out of the question, and since this material must have been deposited in an embayment of the ice, it seems best to correlate it with the lower Wekepeke outlet. The same expansion of the Wekepeke stage would explain the modified drift extending up the valley of the North Nashua as far as Fitchburg. All of this harmonizes well with the idea that the ice margin receded northeastward across this region, maintaining a general northwest and southeast trend.

When the ice retreated from the divide at East Pepperell, with an elevation of about 200 feet, the Ayer outlet across a broad barrier of till at an elevation of 260 to 280 feet was abandoned, and the history of Lake Nashua practically came to an end. In the course of postglacial time the river has trenched the deposits formed in the successive stages of the glacial lake, first grading its channel and then steadily widening its flood plain, where not hemmed in by the hard rocks or masses of bowlder clay.

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CONTENTS

		PAGE
The Rectangular System of United States Public Land Surveying	*Charles L. Du Bois*	259
On the Necessity of Cultivating Water Bacteria in an Atmosphere Saturated with Moisture	*George C. Whipple*	276
Silica Standards for the Determination of Turbidity in Water	*George C. Whipple*, *Daniel D. Jackson*	283
Geological History of the Nashua Valley during the Tertiary and Quaternary Periods	*W. O. Crosby*	288
Review of American Chemical Research		99 to 157

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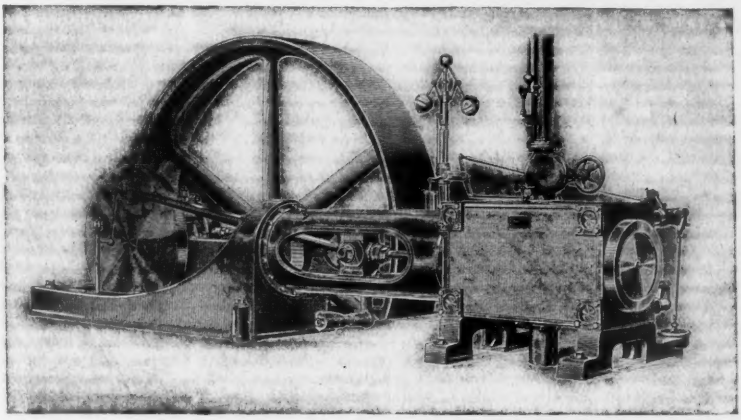

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